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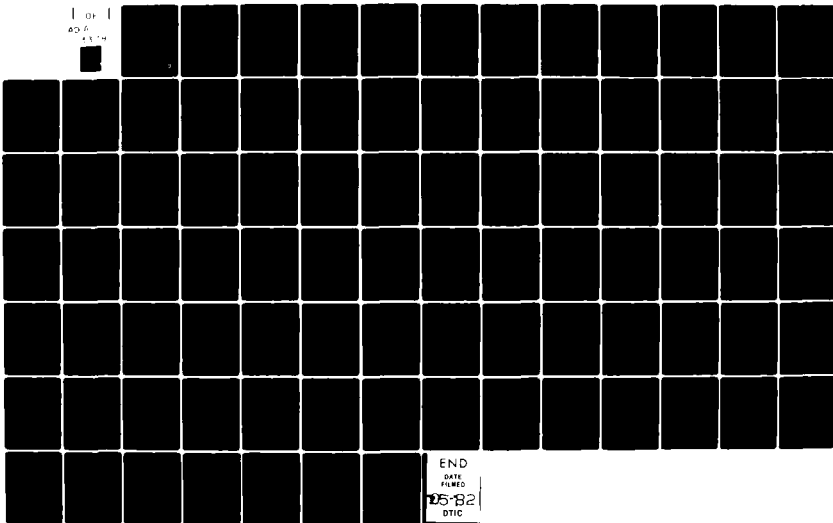
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A NUMERICAL INVESTIGATION OF THE DYNAMICS OF LIQUID SPRAY.(U)
MAR 82 P WEINACHT, J BUCHLIN AFOSR-81-0117

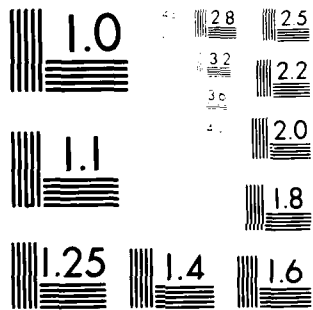
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An axisymmetric numerical model of a liquid spray is presented. The model consists of coupled sets of partial differential equations for the gas phase and ordinary differential equations for the liquid phase. A numerical method based on the MAC method is presented and calculations show good agreement with experiment. The effect of a ceiling on the entrainment performance of a spray is found to be negligible. The examination of the calculated pressure field shows that pressure does not play an important role in the flow and may be ignored. This is in agreement with experiment and contributes additional validation to existing models which ignore this effect.

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Winston K. Pendleton

WINSTON K. PENDLETON
Lt Colonel, USAF
Chief Scientist

Gordon L. Hermann

GORDON L. HERMANN
Lt Colonel, USAF
Deputy Commander

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ABSTRACT

An axisymmetric numerical model of a liquid spray is presented. The model consists of coupled sets of partial differential equations for the gas phase and ordinary differential equations for the liquid phase. A numerical method based on the MAC method is presented and calculations show good agreement with experiment. The effect of a ceiling on the entrainment performance of a spray is found to be negligible. The examination of the calculated pressure field shows that pressure does not play an important role in the flow and may be ignored. This is in agreement with experiment and contributes additional validation to existing models which ignore this effect.

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LIST OF SYMBOLS

C_D	drag coefficient of a sphere
C_N	nozzle design parameter
d_0	inside diameter of nozzle (mm)
D	droplet diameter (mm)
D_t	diameter of spray envelope (m)
f_p	fraction of mass flow through the nozzle assigned to given trajectory
f_r	radial component of drag force acting on droplet (N)
f_z	axial component of drag force acting on droplet (N)
F_r	radial volume force term of momentum source (N/m ³)
F_{rav}	average radial force acting on a particle in source cell (N)
F_z	axial volume force term of momentum source (N/m ³)
g	acceleration of gravity (m/s ²)
H_ℓ	spray height (m)
m	droplet mass (kg)
N	unit normal to boundary
N_p	number of particles in source cell at given instant in time
P	pressure (N/m ²)
ΔP_N	water delivery pressure (N/m ²)
Q_a	volume flow of air entrained into spray (m ³ /min)
Q_w	volume flow of liquid through spray nozzle (l/min)
r	variable of integration inside spray envelope
r_0	radial coordinate of particle trajectory
R	radial coordinate
Re	Reynolds number
RE	Reynolds number of nondimensionalization

t	time	(sec)
u_r	radial velocity of particle	(m/s)
u_z	axial velocity of particle	(m/s)
U_0	particle injection velocity	(m/s)
V_r	radial component of velocity	(m/s)
V_z	axial component of velocity	(m/s)
Z	axial coordinate	(m)
Z_0	axial coordinate of particle trajectory	(m)
ρ	density of gas	(kg/m ³)
ρ_L	density of liquid	(kg/m ³)
θ	initial angle of ejection of particle	(degrees)
θ_{max}	maximum initial angle of particle ejection	(degrees)
η	efficiency of spray	
δs	arc length of trajectory in source cell	
δt	time for particle to pass through source cell	
ν	kinematic viscosity of gas	(m ² /s)
Δ	indicates incremental quantity	

1. INTRODUCTION

The application of liquid sprays is made in many different fields. Examples of a few are fire suppression, combustion, ventilation, and the dispersion of heavy, possibly toxic or flammable, gases. Interest at VKI in the applicability of water sprays for use as water curtains for the dispersion of heavy gases has mandated a need for better prediction methods for the analysis/design of water sprays.

The configuration for the spray to be analysed in this study is shown in figure 1. Liquid particles are ejected through a nozzle into an environment which is at rest in the absence of the spray. The aerodynamic drag acting on the liquid particles results in a loss in momentum of the particles. Since momentum must be conserved, the momentum loss is translated into a momentum gain by the fluid, causing the fluid to be set in motion. Air is thereby entrained into the spray (in much the same way as a jet) resulting in a two phase plume.

Modeling of this phenomenon has been done in the past. A one dimensional model (Refs. 3,5) has been developed at VKI and has shown good results though its applicability for the inclusion of boundary effects is limited. Two dimensional models, existing in the literature (Refs. 1,4,7), are much more able to handle the effects of boundaries. In this light, it is found desirable to have such a two dimensional model at VKI to complement the range of applicability of the existing one dimensional model. Thus, this project concerns the implementation of an axisymmetric numerical model into a computer code. The basic approach is similar to that followed in references 1 and 4.

In this report the model used is outlined, the numerical method for the solution of the model equations is described, and, finally, the results presented and discussed. The implemented computer code is included as an appendix to this report.

2. THE SPRAY MODEL

2.1 Introduction

The model of the spray consists of two distinct sets of equations, one set governing the gas phase and another governing the liquid phase. Linkage between these two sets of equations accounts for the following two physical phenomena : the first concerns the momentum transfer between liquid phase and gas phase, while the second involves the modification of the particle trajectories by the motion of the gas phase.

The gas phase may be modelled as a continuum using an Eulerian approach while the liquid phase, using a Lagrangian approach is modelled by considering a finite set of particles of varying size/initial trajectory.

2.2 The gas phase model

2.2.1 Gas phase equations

Since the gas phase occupies the most significant portion of the flow domain, it may be treated as a continuum. Making the standard assumptions of incompressibility and Newtonian fluid the following form of the Navier Stokes equations may be used. Here, due to the axisymmetric nature of the problem, the equations are written in cylindrical coordinates :

Continuity

$$\frac{1}{R} \frac{\partial}{\partial R} (RV_r) + \frac{\partial V_z}{\partial z} = 0 \quad (2.1)$$

Momentum

r-component

$$V_r \frac{\partial V_r}{\partial R} + V_z \frac{\partial V_r}{\partial z} = - \frac{\partial P}{\partial R} + \nu \left[\frac{\partial}{\partial R} \left(\frac{1}{R} \frac{\partial}{\partial R} (R V_r) \right) + \frac{\partial^2 V_r}{\partial z^2} \right] + F_r \quad (2.2)$$

z-component

$$V_r \frac{\partial V_z}{\partial R} + V_z \frac{\partial V_z}{\partial z} = - \frac{\partial P}{\partial z} + \nu \left[\frac{1}{R} \frac{\partial}{\partial R} \left(R \frac{\partial V_z}{\partial R} \right) + \frac{\partial^2 V_z}{\partial z^2} \right] + F_z \quad (2.3)$$

where V_r , V_z , P are the radial and axial component of velocity, and the pressure respectively; R and z are the radial and axial coordinate and ρ and ν represent the fluid density and kinematic viscosity. The terms F_r and F_z are the volume force terms which account for the contribution of momentum per unit volume from the liquid phase.

2.2.2 Boundary conditions for the gas phase

Considered here are three types of boundaries; a single axis of symmetry boundary, free boundaries and wall boundaries. These are shown in figure 1.

Velocity boundary conditions

Axis of symmetry

At the axis of symmetry the radial component of velocity must be equal to zero because of mass conservation and the symmetry assumption. Symmetry also requires that there be no shear stress in the axial direction, requiring the derivative of the axial velocity with respect to the radial coordinate to be zero.

$$V_r = 0 \quad (2.4)$$

$$\frac{\partial V_z}{\partial R} = 0 \quad (2.5)$$

Wall boundary

Along the wall boundaries the usual conditions for an impermeable, non-slip wall are used :

$$V_r = V_z = 0 \quad (2.6)$$

Free boundary

In the flow domain considered the free boundary is taken to be far from the spray domain. With this assumption the following approximate conditions may be applied. The velocity tangential to the boundary is small, and may be assumed equal to zero. Applying continuity, the boundary condition for the component of velocity normal to the boundary may be obtained.

Vertical free boundary

$$V_z = 0 \quad (2.7)$$

$$\frac{\partial (RV_r)}{\partial R} = 0 \quad (2.8)$$

Horizontal free boundary

$$V_r = 0 \quad (2.9)$$

$$\frac{\partial V_z}{\partial R} = 0 \quad (2.10)$$

Pressure boundary conditions

The pressure boundary conditions may be derived from the momentum equations 2.2 and 2.3. Since most gases have small viscosity it is permissible here to ignore the viscous terms of the momentum equations in deriving the pressure boundary conditions.

The resulting derivation shows that for the wall and axis of symmetry boundaries, the normal derivative of the pressure is equal to zero.

The resulting boundary condition on the free boundary is a bit more complicated using this approach. However, making use of experimental observation which has shown that variation of the pressure field is small throughout the flow domain, the pressure at the free boundary is assumed to be constant.

Wall or axis of symmetry

$$\frac{\partial P}{\partial N} = 0 \quad (2.11)$$

Free boundary

$$P = P_{ref} \quad (2.12)$$

2.3 The particle phase model

2.3.1 Particle equations

The liquid phase is modelled as a distribution of droplets of distinct sizes and trajectories. Using a Lagrangian approach individual particles are followed from injection until hitting the floor. By considering the number of particles of similar sizes/trajectories, the magnitude of droplet-gas

momentum exchange throughout the flow field may be determined. This approach assumes that the particles do not interact with each other, i.e., no collisions or particle break up. Making the additional assumptions that the particles are spherical and non-evaporating, the following equations of motion may be written.

$$m \frac{du_r}{dt} = - f_r \quad (2.13)$$

$$m \frac{du_z}{dt} = - f_z \pm mg \quad (2.14)$$

$$\frac{dr_0(t)}{dt} = u_r \quad (2.15)$$

$$\frac{dz_0(t)}{dt} = u_z \quad (2.16)$$

where u_r , u_z are the particle radial and axial velocities and r_0 and z_0 are the radial and axial position of the particles. "m" is the mass of the particle calculated as follows :

$$m = \rho_L \frac{\pi}{6} D^3 \quad (2.17)$$

where ρ_L is the density of the liquid and D is the particle diameter. f_r and f_z are the radial and axial component of drag force, related to F_r and F_z in equations 2.2 and 2.3 and are calculated as follows :

$$f_r = C_D \operatorname{Re} \frac{\pi D^3 \rho}{8} (u_r - V_r) \quad (2.18)$$

$$f_z = C_D \operatorname{Re} \frac{\pi D^3 \rho}{8} (u_z - V_z) \quad (2.19)$$

Re is the Reynolds number defined as

$$Re = \frac{\sqrt{(u_z - V_z)^2 + (u_r - V_r)^2} D}{\nu} \quad (2.20)$$

The drag coefficient C_D is calculated using a standard form fit for the drag coefficient of a sphere :

$$C_D = \frac{24}{Re} + \frac{6.}{1 + \sqrt{Re}} + .4 \quad (2.21)$$

2.3.2 Initial conditions for the particle equations

The initial conditions are derived from the properties of the spray nozzle. By definition the coordinate system is fixed at the nozzle so the initial conditions for equations 2.15 and 2.16 are simply :

$$r_0(0) = z_0(0) = 0 \quad (2.22)$$

The initial conditions for the force equations are derived by considering the particle ejection velocity from the nozzle and the initial angle of ejection (see figure 2) :

$$\begin{aligned} u_r(0) &= U_0 \sin \theta \\ u_z(0) &= U_0 \cos \theta \end{aligned} \quad (2.23)$$

U_0 is calculated from the volume flow of the nozzle, Q_w :

$$U_0 = \frac{Q_w}{\frac{\pi}{4} d_0^2} \quad (2.24)$$

where d_0 is the inside diameter of the nozzle. The initial angle of ejection of the particle must be between 0 and θ_{\max} . θ_{\max} and d_0 are available from the manufacturers data.

2.3.3 Particle size

Particle size is calculated by using the following expression

$$D = C_N \frac{d_0^{2/3}}{\Delta P_N^{1/3}} \quad (2.25)$$

where C_N is a nozzle design parameter and ΔP_N is the water delivery pressure. These values may be determined from experiment or from manufacturers data.

2.4 Nondimensionalization of the model equations

To allow the resulting program to be used easily with any system of units, the model equations are nondimensionalized.

Velocities are nondimensionalized by the particle ejection velocity

$$\hat{V}_r = \frac{V_r}{U_0}, \quad \hat{V}_z = \frac{V_z}{U_0}, \quad \hat{u}_r = \frac{u_r}{U_0}, \quad \hat{u}_z = \frac{u_z}{U_0} \quad (2.26)$$

Pressure is non dimensionalized by the gas density, and the particle ejection velocity squared

$$\hat{P} = \frac{P}{\rho U_0^2} \quad (2.27)$$

Lengths are nondimensionalized by the spray height, H_ℓ , (see figure 1)

$$\hat{R} = \frac{R}{H_\ell}, \quad \hat{z} = \frac{z}{H_\ell}, \quad \hat{r}_0 = \frac{r_0}{H_\ell}, \quad \hat{z}_0 = \frac{z_0}{H_\ell} \quad (2.28)$$

Time is nondimensionalized by the spray height divided by the ejection velocity

$$\hat{t} = \frac{tU_0}{H_\ell} \quad (2.29)$$

The momentum source terms are nondimensionalized by the ejection velocity squared divided by the spray height

$$\hat{F}_r = F_r \frac{H_\ell}{U_0^2}, \quad \hat{F}_z = F_z \frac{H_\ell}{U_0^2} \quad (2.30)$$

Thus in the momentum equations (2.2) and (2.3), the viscosity is replaced by the reciprocal of the "Reynolds number of nondimensionalization"

$$\frac{1}{RE} = \frac{\nu}{U_0 H_\ell} \quad (2.31)$$

The nondimensionalization of the other model equations is straightforward. From this point on, the model equations are assumed nondimensional, and the hat ($\hat{}$) is neglected.

3. THE NUMERICAL METHOD

3.1 Introduction

It is difficult indeed to conceptualize a numerical method for the simultaneous solution of both sets of equations. A more natural method of solution involves iterative solution of these equations. Such an iterative solution is outlined by the flow chart in figure 3.

The specific numerical method to solve each set of equations differs due to their nature (ODE, PDE) and are considered in appropriate sections.

3.2 Numerical solution of the particle equations

The solution of the set of ordinary differential equations (ODE) governing the particle phase is made by a simultaneous fourth order Runge-Kutta technique which is well documented in the literature (Ref. 9).

3.3 Numerical solution of the gas equations

The numerical scheme for the solution of the gas phase equations is based on the MAC method (Refs. 8,10,11).

The gas phase equations are recast into the following form

$$\begin{aligned} \frac{\partial V_r}{\partial t} + \frac{1}{R} \frac{\partial}{\partial R} (V_r^2 R) + \frac{\partial (V_r V_z)}{\partial z} = - \frac{\partial P}{\partial R} + \\ + \frac{1}{RE} \left[\frac{\partial^2 V_r}{\partial R^2} + \frac{\partial}{\partial R} \left(\frac{V_r}{R} \right) + \frac{\partial^2 V_r}{\partial z^2} \right] + F_r \end{aligned} \quad (3.1)$$

$$\begin{aligned} \frac{\partial V_z}{\partial t} + \frac{1}{R} \frac{\partial}{\partial R} (V_r V_z R) + \frac{\partial V_z^2}{\partial z} = - \frac{\partial P}{\partial z} + \\ + \frac{1}{RE} \left[\frac{1}{R} \frac{\partial V_z}{\partial R} + \frac{\partial^2 V_z}{\partial R^2} + \frac{\partial^2 V_z}{\partial z^2} \right] + F_z \end{aligned} \quad (3.2)$$

$$\begin{aligned} \frac{1}{R} \frac{\partial P}{\partial R} + \frac{\partial^2 P}{\partial R^2} + \frac{\partial^2 P}{\partial z^2} = - \frac{\partial D}{\partial t} - \frac{\partial^2 (V_r)^2}{\partial R^2} - \frac{\partial^2 (V_z)^2}{\partial z^2} \\ - \frac{2}{R} \frac{\partial}{\partial R} (V_r)^2 - \frac{2}{R} \frac{\partial}{\partial z} (V_z V_r) - 2 \frac{\partial^2 (V_r V_z)}{\partial R \partial z} + \\ + \frac{1}{RE} \left[\frac{1}{R} \frac{\partial D}{\partial R} + \frac{\partial^2 D}{\partial R^2} + \frac{\partial^2 D}{\partial z^2} \right] + \frac{1}{R} \frac{\partial (R F_r)}{\partial R} + \frac{\partial F_z}{\partial z} \end{aligned} \quad (3.3)$$

These equations are written in unsteady form as the MAC solution procedure is an iterative one in which the steady state solution is the desired solution. To be noted here is the exchange of the continuity equation for a Poisson equation for the pressure. Contained in this Poisson equation is the variable D which is a dilation term representing the amount of continuity existing.

$$D = \frac{1}{R} \frac{\partial (V_r R)}{\partial R} + \frac{\partial V_z}{\partial z} \quad (3.4)$$

This term is used to reduce the nonlinear instabilities existing in the numerical solution of the Navier-Stokes equations (Ref. 11). Continuity is solved implicitly using this term.

3.3.1 Discretization of the MAC method equations

An appropriate discretization of the MAC method equation on a staggered grid (see Fig. 4) is given below :

$$\begin{aligned}
 \tilde{v}_{r,i+1/2,j} = v_{r,i+1/2,j} + \Delta t & \left[- \frac{1}{R_{i+1/2} \Delta R} \left\{ v_{r,i+1,j}^2 R_{i+1} - v_{r,i,j}^2 R_i \right\} \right. \\
 & - \frac{1}{\Delta z} \left\{ v_r v_{z,i+1/2,j+1/2} - v_r v_{z,i+1/2,j-1/2} \right\} \\
 & - \frac{1}{\Delta R} \left\{ p_{i+1,j} - p_{i,j} \right\} + \frac{1}{RE} \left[\frac{1}{2\Delta R} \left\{ \left(\frac{v_r}{R} \right)_{i+3/2,j} \right. \right. \\
 & \left. \left. - \left(\frac{v_r}{R} \right)_{i-1/2,j} \right\} + \frac{v_{r,i+3/2,j} - 2v_{r,i+1/2,j} + v_{r,i-1/2,j}}{\Delta R^2} \right. \\
 & \left. \left. + \frac{v_{r,i+1/2,j+1} - 2v_{r,i+1/2,j} + v_{r,i+1/2,j-1}}{\Delta z^2} \right] + F_r \right\}
 \end{aligned}
 \tag{3.5}$$

$$\begin{aligned}
 \tilde{V}_{z,i,j+1/2} = & V_{z,i,j+1/2} + \Delta t \left\{ \frac{-1}{R_i \Delta R} \left[V_r V_{z,i+1/2,j+1/2} R_{i+1/2} \right. \right. \\
 & - \left. \left. V_r V_{z,i-1/2,j+1/2} R_{i-1/2} \right] - \frac{1}{\Delta z} \left[V_{z,i,j+1}^2 - V_{z,i,j}^2 \right] \right. \\
 & - \frac{1}{\Delta z} \left[P_{i,j+1} - P_{i,j} \right] + \\
 & + \frac{1}{RE} \left[\frac{1}{R_i} \left[\frac{V_{z,i+1,j+1/2} - V_{z,i-1,j+1/2}}{2\Delta R} \right] \right. \\
 & + \frac{V_{z,i+1,j+1/2} - 2V_{z,i,j+1/2} + V_{z,i-1,j+1/2}}{\Delta R^2} \\
 & \left. + \frac{V_{z,i,j+1/2} - 2V_{z,i,j+1/2} + V_{z,i,j-1/2}}{\Delta z^2} \right] + F_z \left. \right\} \quad (3.6)
 \end{aligned}$$

$$\begin{aligned}
 \frac{1}{R_i} & \frac{\tilde{P}_{i+1,j} - \tilde{P}_{i-1,j}}{2\Delta R} + \frac{\tilde{P}_{i+1,j} - 2\tilde{P}_{i,j} + \tilde{P}_{i-1,j}}{\Delta R^2} + \frac{\tilde{P}_{i,j+1} - 2\tilde{P}_{i,j} + \tilde{P}_{i,j-1}}{\Delta z^2} = \\
 & = - \frac{\tilde{V}_{r,i+1,j}^2 - 2\tilde{V}_{r,i,j}^2 + \tilde{V}_{r,i-1,j}^2}{\Delta R^2} - \frac{\tilde{V}_{z,i,j+1}^2 - 2\tilde{V}_{z,i,j}^2 + \tilde{V}_{z,i,j-1}^2}{\Delta z^2}
 \end{aligned}$$

$$\begin{aligned}
 & - \frac{2}{R_i} \frac{V_{r,i+1,j}^2 - V_{r,i,j}^2}{2\Delta R} - \frac{2}{R_i} \frac{V_{z,i,j+1} V_{r,i,j+1} - V_{z,i,j-1} V_{r,i,j-1}}{2\Delta z} \\
 & - 2 \frac{V_r V_{z,i+1/2,j+1/2} + V_r V_{z,i-1/2,j-1/2} - V_r V_{z,i+1/2,j-1/2} - V_r V_{z,i-1/2,j+1/2}}{\Delta R \Delta z} \\
 & + \frac{1}{RE} \left[\frac{1}{R_i} \frac{D_{i+1,j} - D_{i-1,j}}{2\Delta R} + \frac{D_{i+1,j} - 2D_{i,j} + D_{i-1,j}}{\Delta R^2} + \frac{D_{i,j+1} - 2D_{i,j} + D_{i,j-1}}{\Delta z^2} \right] \\
 & + \frac{D_{i,j}}{\Delta t} + \frac{1}{R_i} \left[\frac{R_{i+1/2} F_{r,i+1/2,j} - R_{i-1/2} F_{r,i-1/2,j}}{\Delta R} \right] + \frac{F_{z,i,j+1/2} - F_{z,i,j-1/2}}{\Delta z}
 \end{aligned}
 \tag{3.7}$$

Here the tilde (~) indicates the updated quantities (N+1 iteration).

As can be seen, the MAC method is a two level scheme involving explicit solution of equations 3.5 and 3.6 for the velocities of the N+1 iteration and an iterative solution of equations 3.7 for the updated pressure field.

Note the discretization of the $\frac{\partial D}{\partial t}$ term. D^{N+1} is set equal to zero in an attempt to force continuity to exist at the N+1 time step. At steady state the time derivative term disappears and continuity will be satisfied, thereby solving the original problem.

This method was applied to the solution of laminar flow in a pipe as a test case. Solutions were obtained for low Reynolds numbers ($Re < 100$) but instabilities were observed for higher Reynolds numbers.

Because the solution of the gas equations involves a low gas viscosity ($\nu = 1.5 \times 10^{-5} \text{ m}^2/\text{s}$) and therefore high Reynolds numbers, the numerical method has to be modified.

3.3.2 Modification to the MAC method

To remove the instabilities upwind differencing was employed. This is not so straightforward for the staggered grid used and involves some additional approximations. The resulting discretization of the momentum equations is made below. Here only the convective terms are affected and therefore are the only ones considered.

$$\frac{\partial V_r}{\partial t} + V_r \frac{\partial V_r}{\partial r} + V_z \frac{\partial V_r}{\partial z}$$

$$\cong \frac{\tilde{V}_{r_{i+1/2,j}} - V_{r_{i+1/2,j}}}{\Delta t}$$

$$+ V_{r_{i+1/2,j}} \left\{ \begin{array}{l} \frac{V_{r_{i+1/2,j}} - V_{r_{i-1/2,j}}}{\Delta r}, V_{r_{i+1/2,j}} > 0 \\ \frac{V_{r_{i+3/2,j}} - V_{r_{i+1/2,j}}}{\Delta r}, V_{r_{i+1/2,j}} < 0 \end{array} \right\}$$

$$V_{ZAU} = \begin{cases} \frac{V_{r_{i+1/2,j+1}} - V_{r_{i+1/2,j}}}{\Delta z}, & V_{ZAU} > 0 \\ \frac{V_{r_{i+1/2,j}} - V_{r_{i+1/2,j-1}}}{\Delta z}, & V_{ZAU} < 0 \end{cases}$$

$$V_{ZAU} = \frac{1}{4} \left\{ V_{z_{i,j+1/2}} + V_{z_{i+1,j+1/2}} + V_{z_{i,j-1/2}} + V_{z_{i+1,j-1/2}} \right\} \quad (3.8)$$

$$\frac{\partial V_z}{\partial t} + V_r \frac{\partial V_z}{\partial r} + V_z \frac{\partial V_z}{\partial z}$$

$$\approx \frac{\tilde{V}_{z_{i,j+1/2}} - V_{z_{i,j+1/2}}}{\Delta t} +$$

$$+ V_{RAU} \begin{cases} \frac{-V_{z_{i+1,j+1/2}} - V_{z_{i,j+1/2}}}{\Delta R}, & V_{RAU} > 0 \\ \frac{V_{z_{i,j+1/2}} - V_{z_{i-1,j+1/2}}}{\Delta R}, & V_{RAU} < 0 \end{cases}$$

$$+ V_{z_{i,j+1/2}} \begin{cases} \frac{V_{z_{i,j+3/2}} - V_{z_{i,j+1/2}}}{\Delta z}, & V_{z_{i,j+1/2}} > 0 \\ \frac{V_{z_{i,j+1/2}} - V_{z_{i,j-1/2}}}{\Delta z}, & V_{z_{i,j+1/2}} < 0 \end{cases} \quad (3.9)$$

The pressure equation remains the same.

This modification allowed a stable solution to be obtained, though the scheme did not allow the lower wall to be sensed, and no recirculation occurred (see Fig. 5). There another modification was employed. This involved changing the unsteady term in the momentum equations along the lower and axis of symmetry boundaries.

$$\frac{\partial V_z}{\partial t} \cong \frac{\tilde{V}_{z,i,j+1/2} - \frac{1}{2} (V_{z,i,j+3/2} + V_{z,i,j-1/2})}{\Delta t} \quad (3.10)$$

on lower boundary,

$$\frac{\partial V_r}{\partial t} \cong \frac{\tilde{V}_{r,i+1/2,j} - \frac{1}{2} (V_{r,i+3/2,j} + V_{r,i-1/2,j})}{\Delta t} \quad (3.11)$$

on axis of symmetry boundary.

This finally yielded plausible results.

3.3.3 Solution procedure for the MAC method

The solution procedure for the MAC method, as mentioned previously, involves an explicit solution of equations (3.5) and (3.6) with the modifications for the velocity field at the N+1 iteration and an iterative solution of (3.7) for the pressure field at the N+1 iteration. This iterative solution was made using a point by point SOR method. The overrelaxation factor used was $\omega = 1.5$, though no optimization has been done on this parameter.

3.4 Calculation of the source terms in the Navier-Stokes equations

For the calculation of the source term, the particle trajectories are superimposed over the mesh used for the solution of the gas equations, (see figure 6). To calculate the source terms the arc length of each particle trajectory in a given cell is determined. Because the velocity along this trajectory is known, the time that a particle spends in this cell can be determined :

$$\delta t = \int \frac{ds}{\sqrt{V_r^2 + V_z^2}} \cong \frac{\delta s}{\sqrt{V_r^2 + V_z^2}} \quad (3.12)$$

for small δs and gradually varying V_r and V_z .

From this time the average number of particles in the cell is determined by considering the fraction of the mass flow through the nozzle assigned to this particular trajectory, f_p . The average force along the arc length is determined and then the contribution to the momentum source term along this trajectory in this particular cell is found as follows.

Number of particles on given trajectory in control volume :

$$N_p = \frac{Q_w \cdot f_p \cdot \delta t}{\frac{\pi}{6} D^3} \quad (3.13)$$

$$F_r = \frac{F_{rav} \times N_p}{\text{Volume of cell}} \quad (3.14)$$

similarly for F_z .

It should be noted that F_r and F_z are not calculated in the same cell because of the staggered grid (see figure 4).

4. RESULTS

Results were obtained for the consideration of the effect of increase of mass flow through the nozzle and the effect of a ceiling on entrainment properties of the spray, and finally, to examine the pressure field. The results were obtained by using the properties of a Lechler SZ1 spray nozzle as input to the program (see Table 1).

4.1 Comparison with experiment

First to validate the program a comparison of the entrainment properties of the calculated spray was made with the experimental results of an unconfined spray. These results are shown in figure 7. Here the entrainment efficiency is plotted versus the inverse of the non dimensional spray envelope diameter squared. The entrainment efficiency is defined as the volume flow of air entrained into the spray divided by the volume flow of water through the nozzle. The amount of air entrained into the spray is defined as follows :

$$Q_a = 2\pi \int_0^{D_t/2} r V_z(r) dr \quad (4.1)$$

Results were obtained by considering a spray nozzle mounted on a ceiling two meters above the floor, for all three mass flows considered. Although this is not an unconfined spray, previous results have shown little effect of the presence of the ceiling (Ref. 6). The axial positions where these results were obtained ranged from 20 percent of the spray height from the nozzle to 55 percent of this distance. It was impossible to calculate these values any closer to the nozzle because of the lack of resolution with 21×21 pressure nodes. At axial positions greater than this the floor seems to have a significant effect on the entrainment, so no comparison is made in this area.

The results displayed in figure 7 show good agreement with the McQuaid correlation (solid line) and the $\pm 20\%$ scatter of experimental data about this line. This gives confidence that the bulk of the flow field is well predicted.

4.2 Effect of increasing mass flow through nozzle

The effect of increasing mass flow is displayed in figures 8, 9 and 10. Here the velocity vectors are non dimensionalized by the ejection velocity of the particle. For the determination of the entrained air flow equation 4.1 is rearranged

$$Q_a = 2\pi U_0 \int_0^{D_t/2} r \frac{V_z(r)}{U_0} dr \propto 2\pi Q_w \int_0^{D_t/2} r \frac{V_z(r)}{U_0} dr \quad (4.2)$$

As can be seen from the results, the flow field non dimensionalized by the ejection velocity does not change significantly. Thus the integral in 4.2 is of the same order of magnitude for all three mass flows considered. It seems that the air entrainment in the spray is increased strongly by increasing the mass flow through the nozzle. This is a physically observable result.

Finally the efficiency of the spray is examined.

$$\eta = \frac{Q_a}{Q_w} = 2\pi \int_0^{D_t/2} r \frac{V_z(r)}{U_0} dr \quad (4.3)$$

Close examination of figures 8, 9 and 10 shows a very slight increase in the efficiency of the spray with increased mass flow, reflected by a slight increase in the above integral. This result is found to be true for some cases, though the inverse can also be true. This is because higher mass flow results in small droplets which exchange momentum with air more rapidly resulting in higher entrainment, but because of the

small droplet size the spray envelope contracts quickly slowing entrainment. Thus, for small spray lengths an increase in efficiency is observed relative to larger droplet sizes, but this is reversed as the spray length is increased.

4.3 Effect of ceiling on entrainment

Results were obtained for the case where the ceiling is removed. These results are shown in figures 11 and 12. Though not shown a free boundary was placed at a height of two meters above the spray nozzle. Comparison with the previous results of corresponding mass flow with ceiling included shows little change in the entrainment properties with or without a ceiling. This result is supported by experimental results (Ref. 3).

4.4 Examination of the pressure field

Along with the velocity field each calculation also gives the corresponding pressure field. The isobars of a typical pressure field are shown in figure 13. This figure validates the previous assumption in the derivation of the boundary condition that at the free boundary the pressure field varies little and the pressure can be set to a reference value.

The area of steepest pressure gradients is near the floor inside the spray envelope. However, the pressure gradient in this region is small compared to the momentum source term. The other area of high pressure gradient seems to be at the nozzle. In this region, again the pressure gradient is small compared to momentum source term inside the spray envelope, though outside the spray envelope the pressure gradient may be significant. Better resolution is necessary to draw a firm conclusion.

It can be concluded that for the bulk of the flow field ignoring the pressure gradient may be a good approximation. This is a particularly important result since the pressure calculations are the most time consuming and require the most number of statements in program. In the future the program may be modified to include only a closed form expression for a pressure-like variable which forces continuity to be satisfied. This should result in large savings in computer time and allow better resolution in the mesh.

5. CONCLUSIONS

It has been shown that the axisymmetric spray model implemented gives good results for the entrainment of air inside the spray envelope for the portion at the spray envelope which contains most of the entrained air. The bulk of the surrounding flow field is thus considered to be more or less correctly predicted.

The physically observable result that increasing the outflow from the nozzle increases entrainment of air is also found.

The effect of the ceiling on entrainment is seen to be negligible.

Finally, the examination of the pressure field indicates that neglecting the pressure gradient is a good approximation for the bulk of the flow field. This result leads to the recommendation that work continues on the model to incorporate a closed form expression for a pressure-like variable to force continuity to hold, while eliminating the need for the Poisson equation for the pressure. This will allow better results since the mesh may be made smaller due to the saving in computer time.

Application of this model to a spray in the upward facing mode is straightforward.

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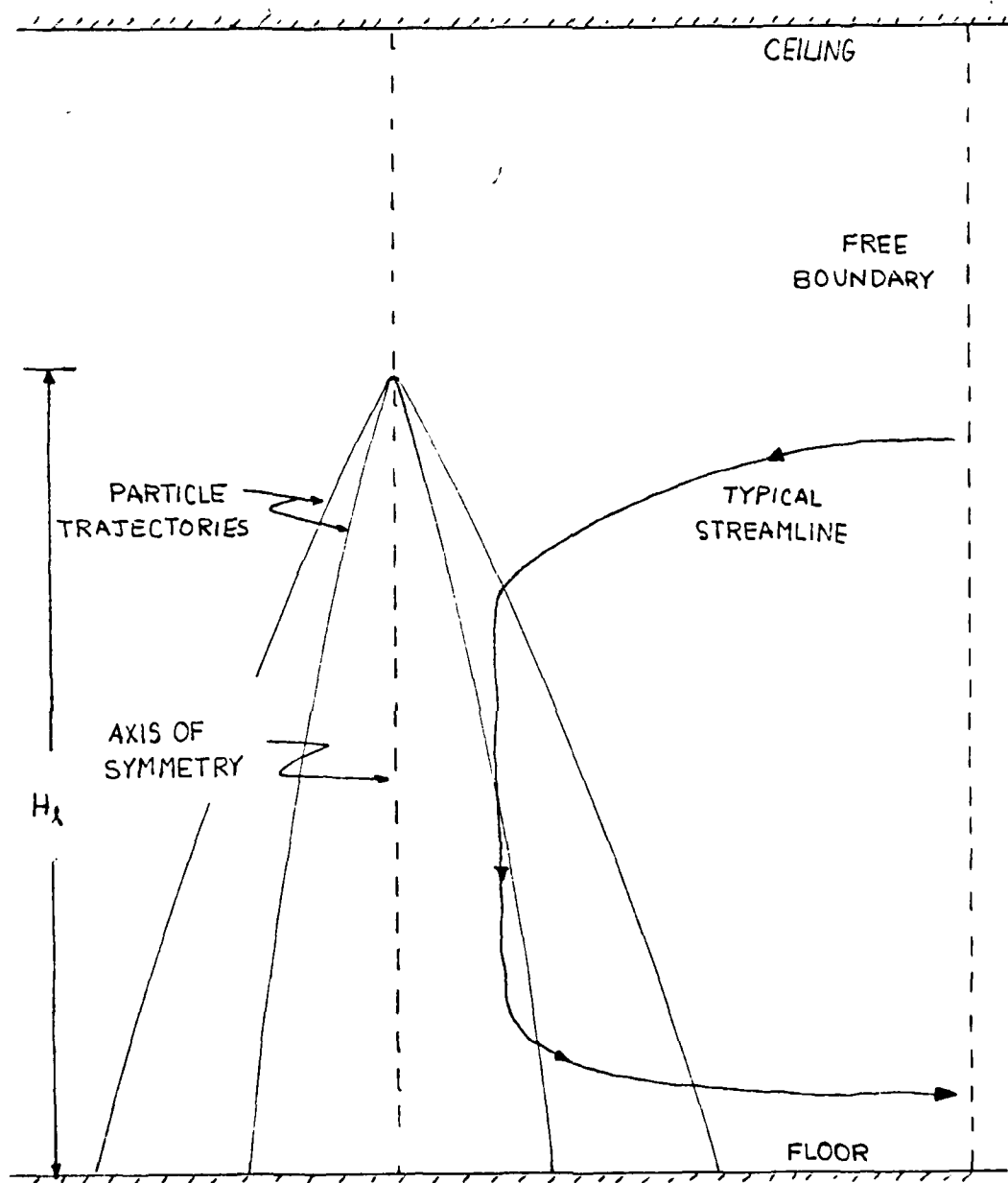


Figure 1 Spray and flow domain in downward facing mode

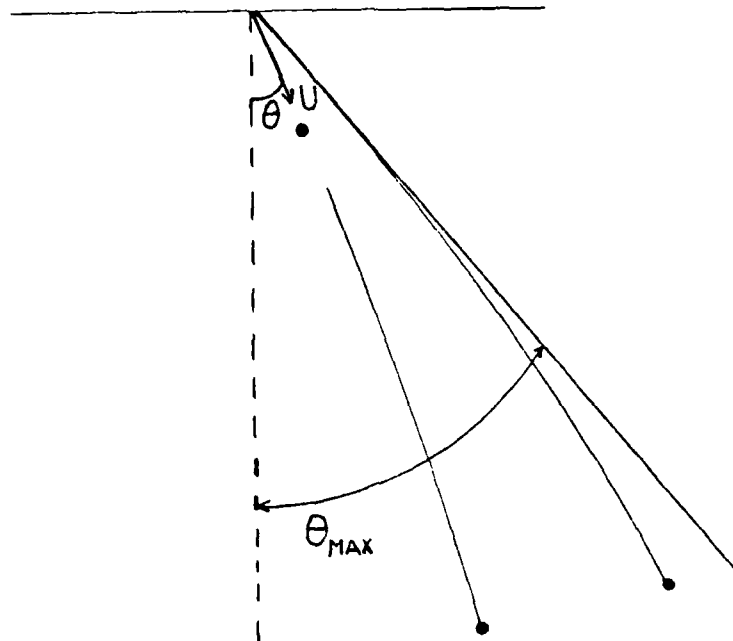


Figure 2 Nozzle Configuration

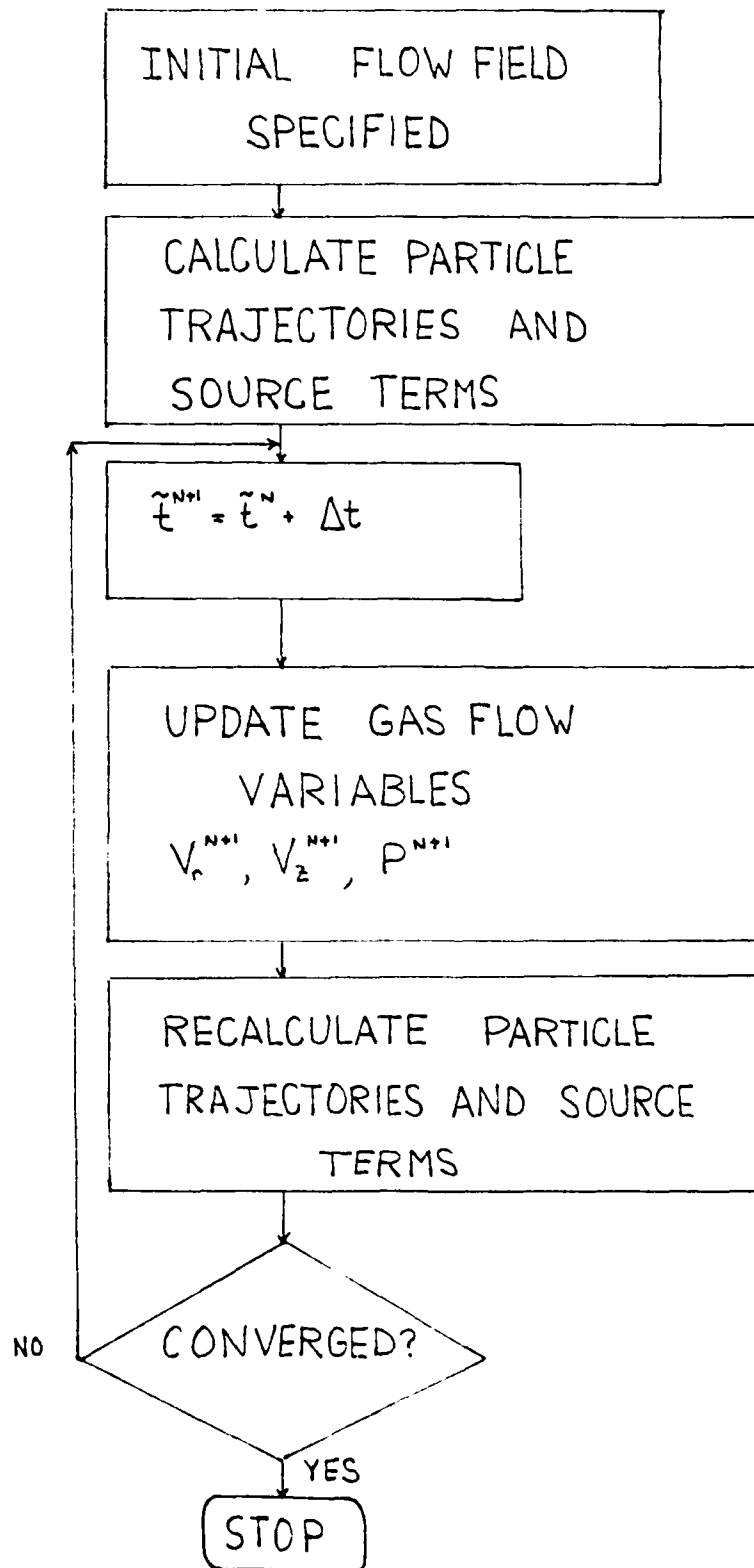


Figure 3 Scheme for numerical solution

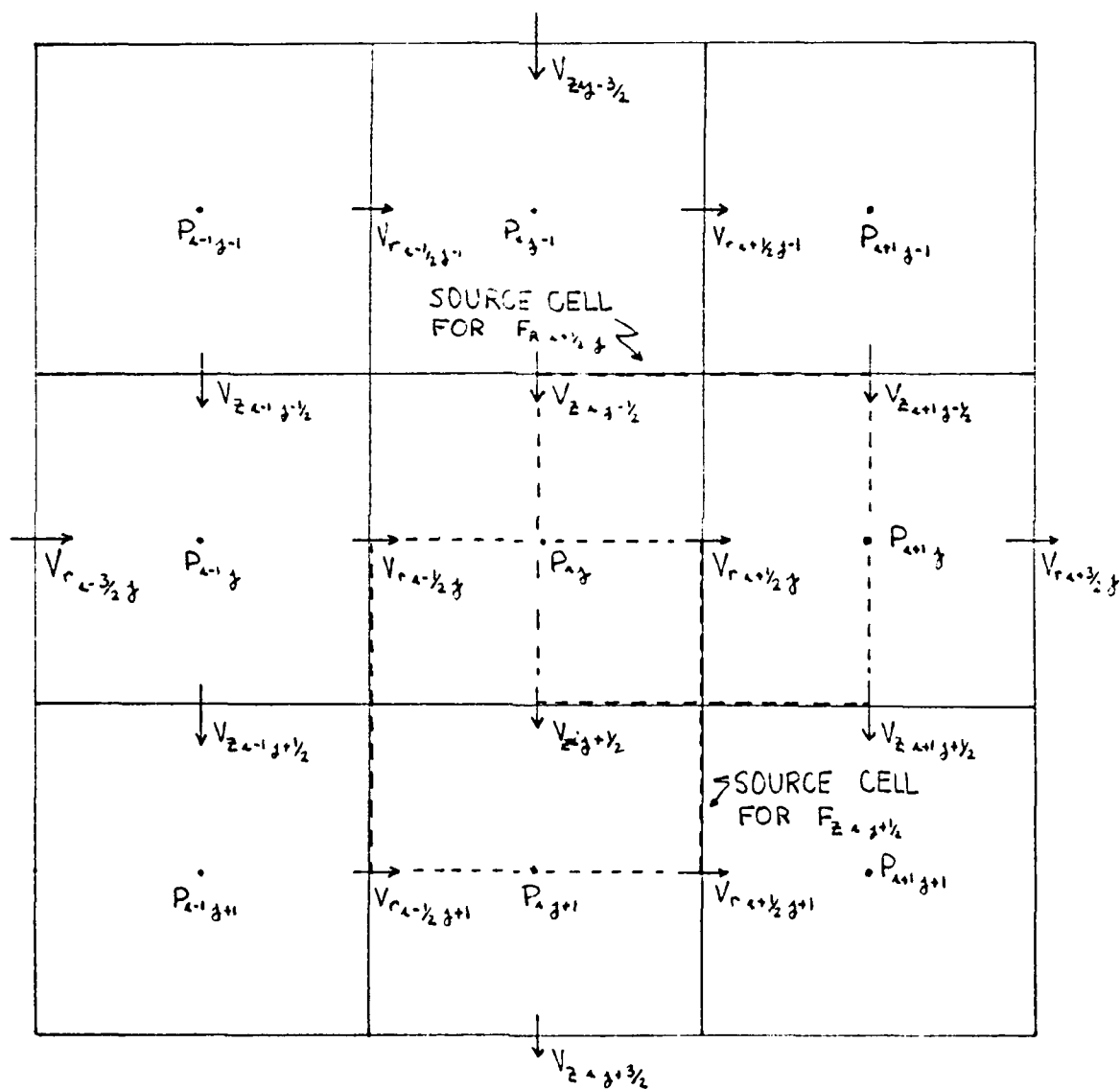


Figure 4 Staggered MAC grid with source cells

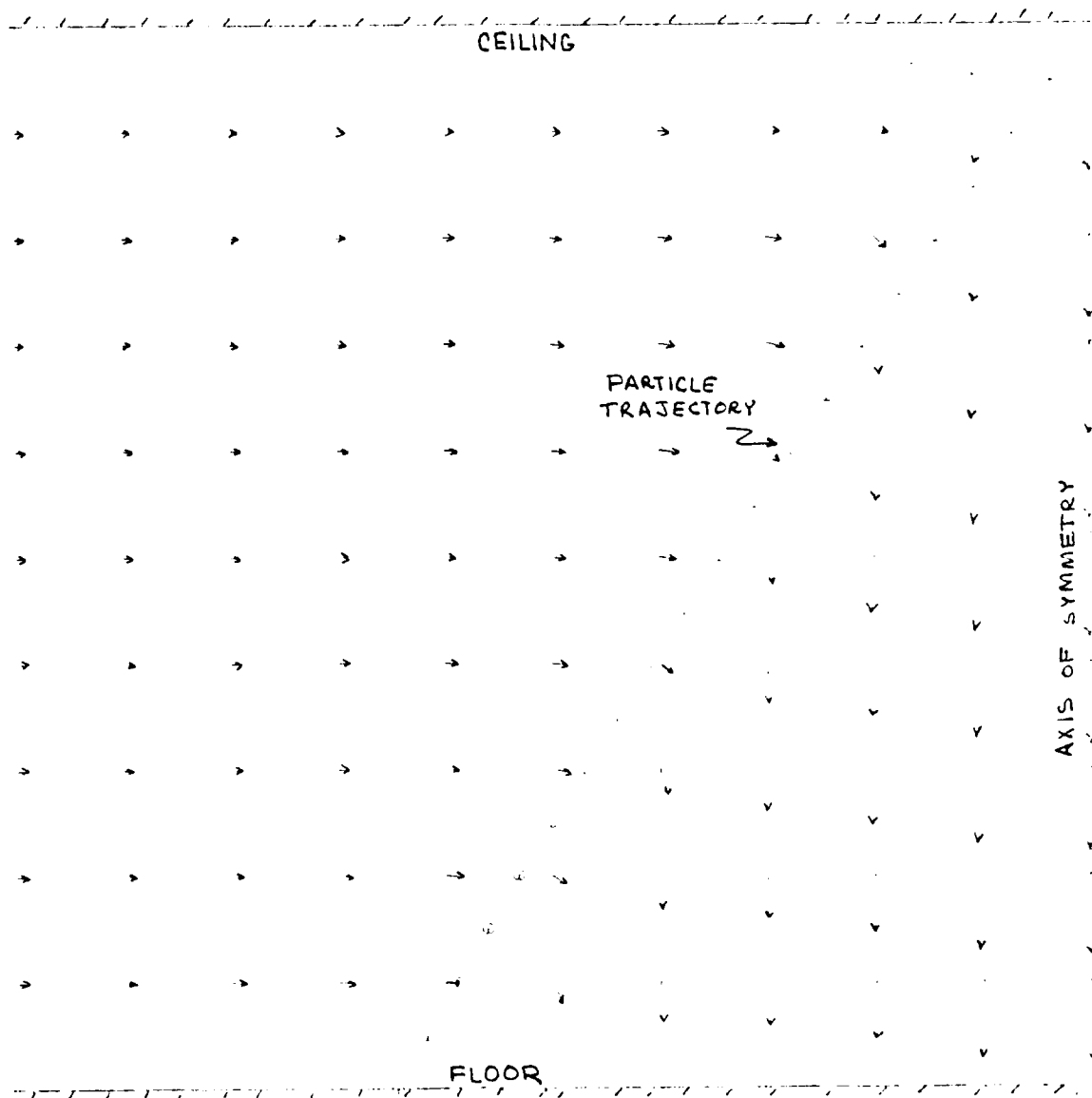


Figure 5 Non-Recirculating Spray

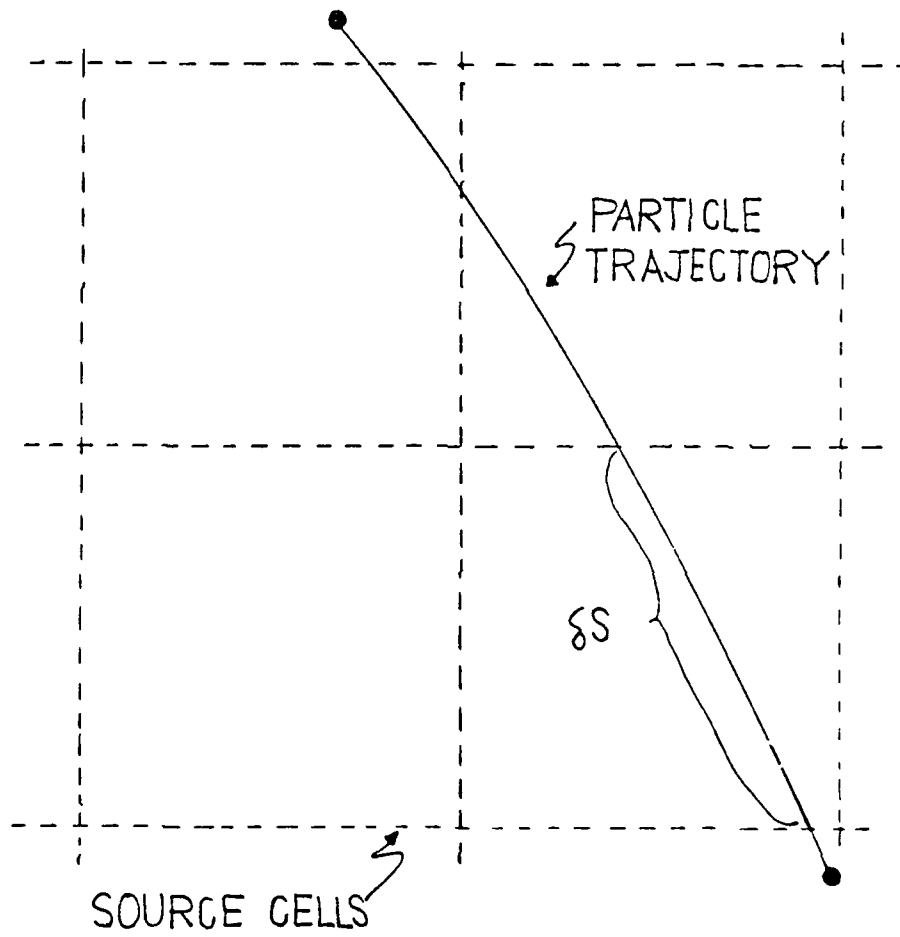


Figure n Particle trajectory superimposed on source cells

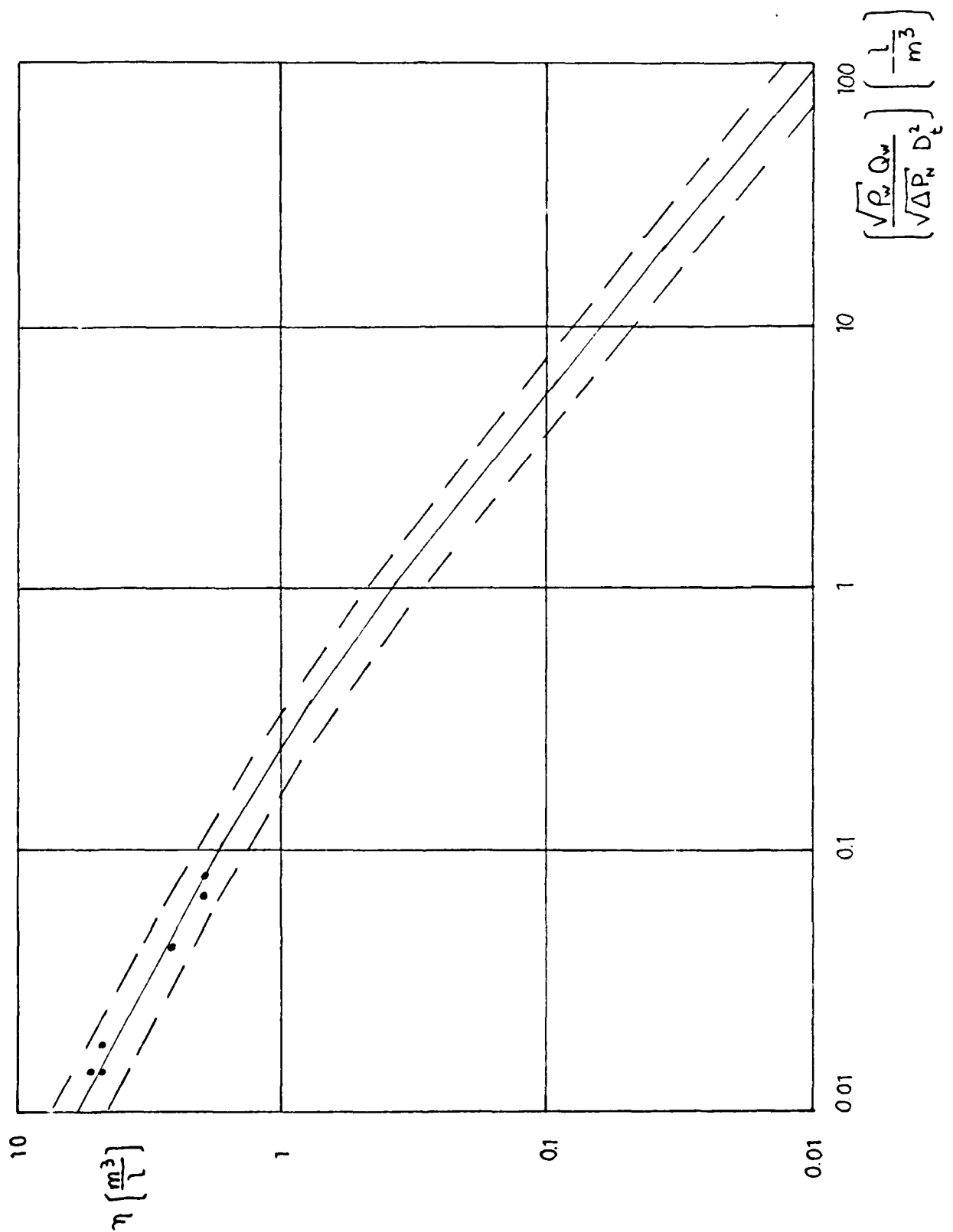
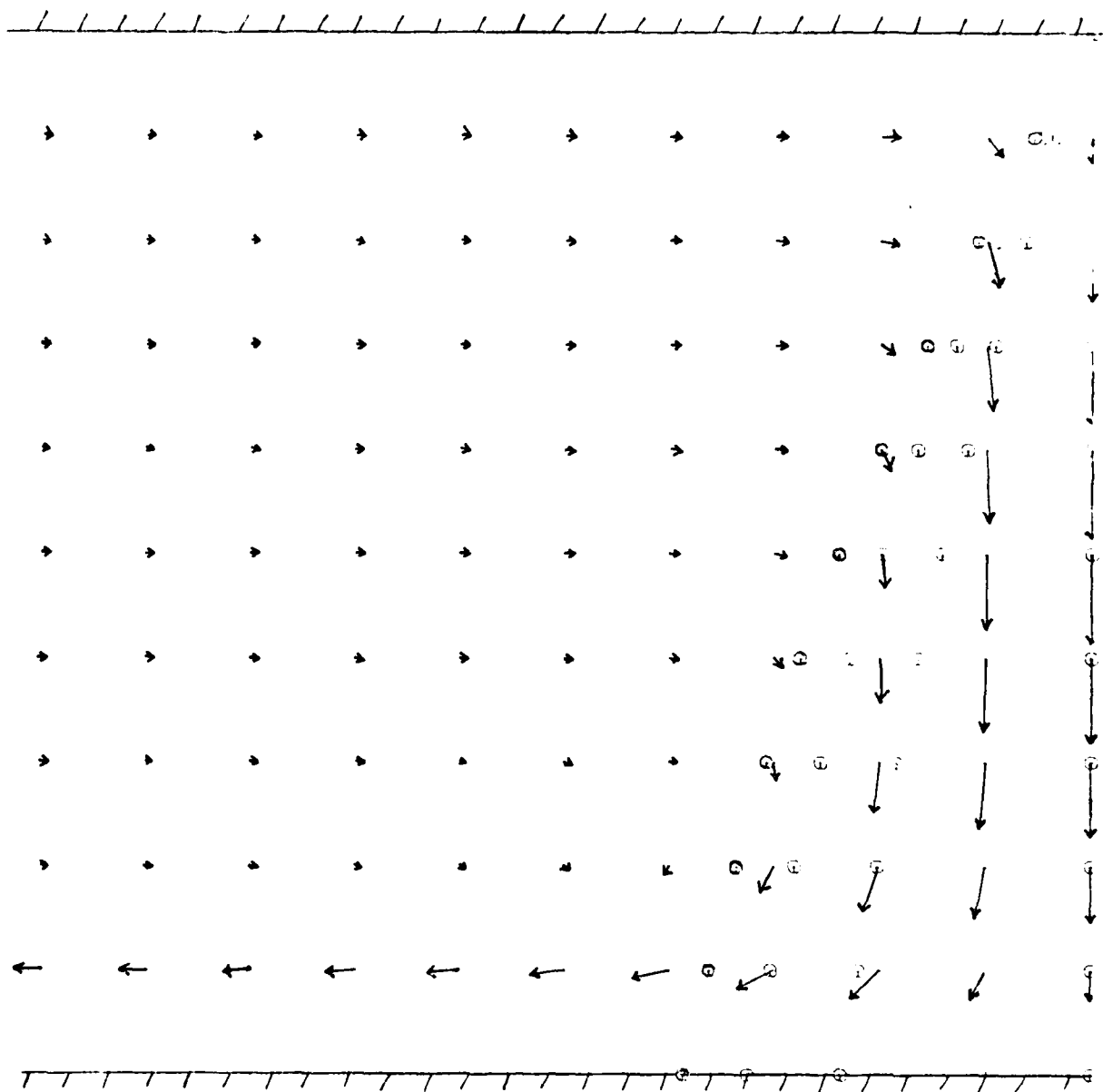


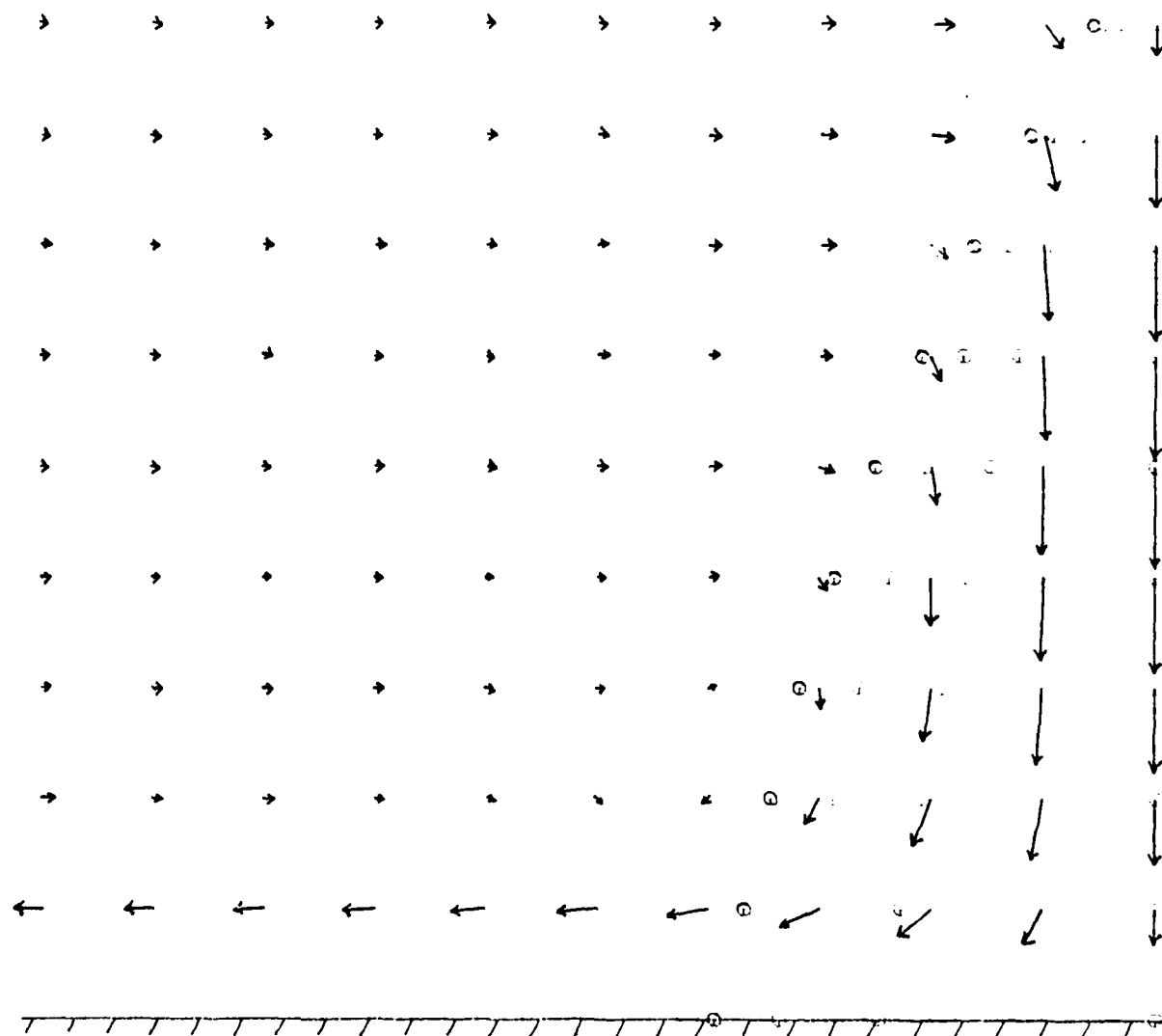
Figure 7 Comparison of air entrainment with experimental results



————— CORRESPOND TO A CAR VELOCITY TO
 INJECTION VELOCITY RATIO OF 10 PERCENT
 ○ ○ ○ ○ REPRESENT PARTICLE TRAJECTORIES

LEHLER 121 NOZZLE
 NOZZLE DIAMETER 1.14 MM
 HALF ANGLE OF SPRAY 30° DEGREE
 LIQUID VOLUME FLOW 4.4 LIT PER MIN
 DROPLET SIZE 1.00 MM
 SPRAY HEIGHT 0.0 M

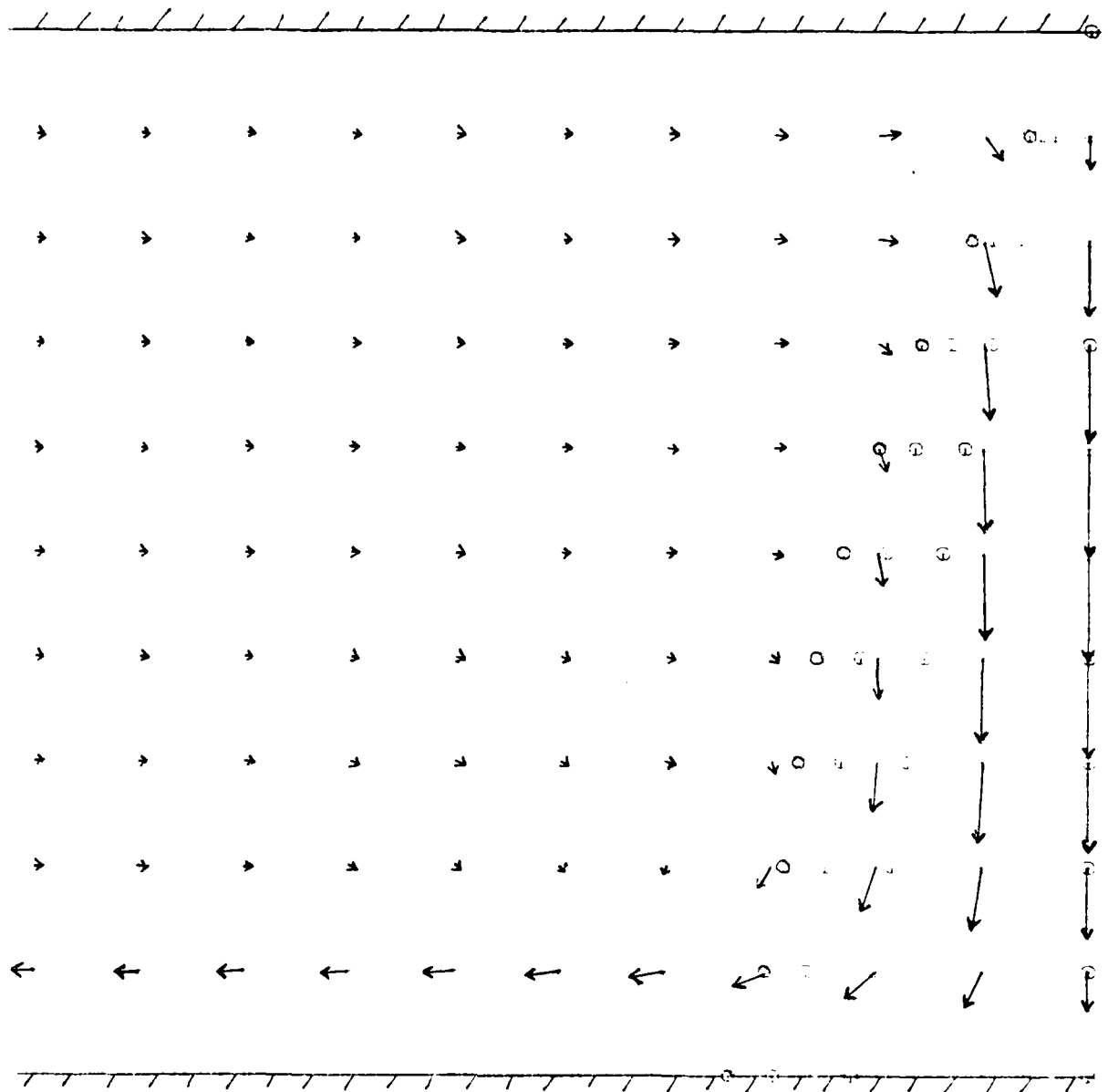
FIG. 8 FLOW FIELD AND PARTICLE TRAJECTORIES



← CORRESPONDS TO A GAS VELOCITY TO
 IMPACT VELOCITY RATIO OF 20 PERCENT
 ○ ○ ○ ○ REPRESENT PARTICLE TRAJECTORIES

LEHLER 21 11 11 F
 NOZZLE DIAMETER 4.40 MM
 HALF ANGLE OF SPRAY 30.0 DEGREES
 LIQUID VOLUME FLOW 10.3 LT PER MIN
 DROPLET SIZE 0.01 MM
 SPRAY HEIGHT 1.00 M

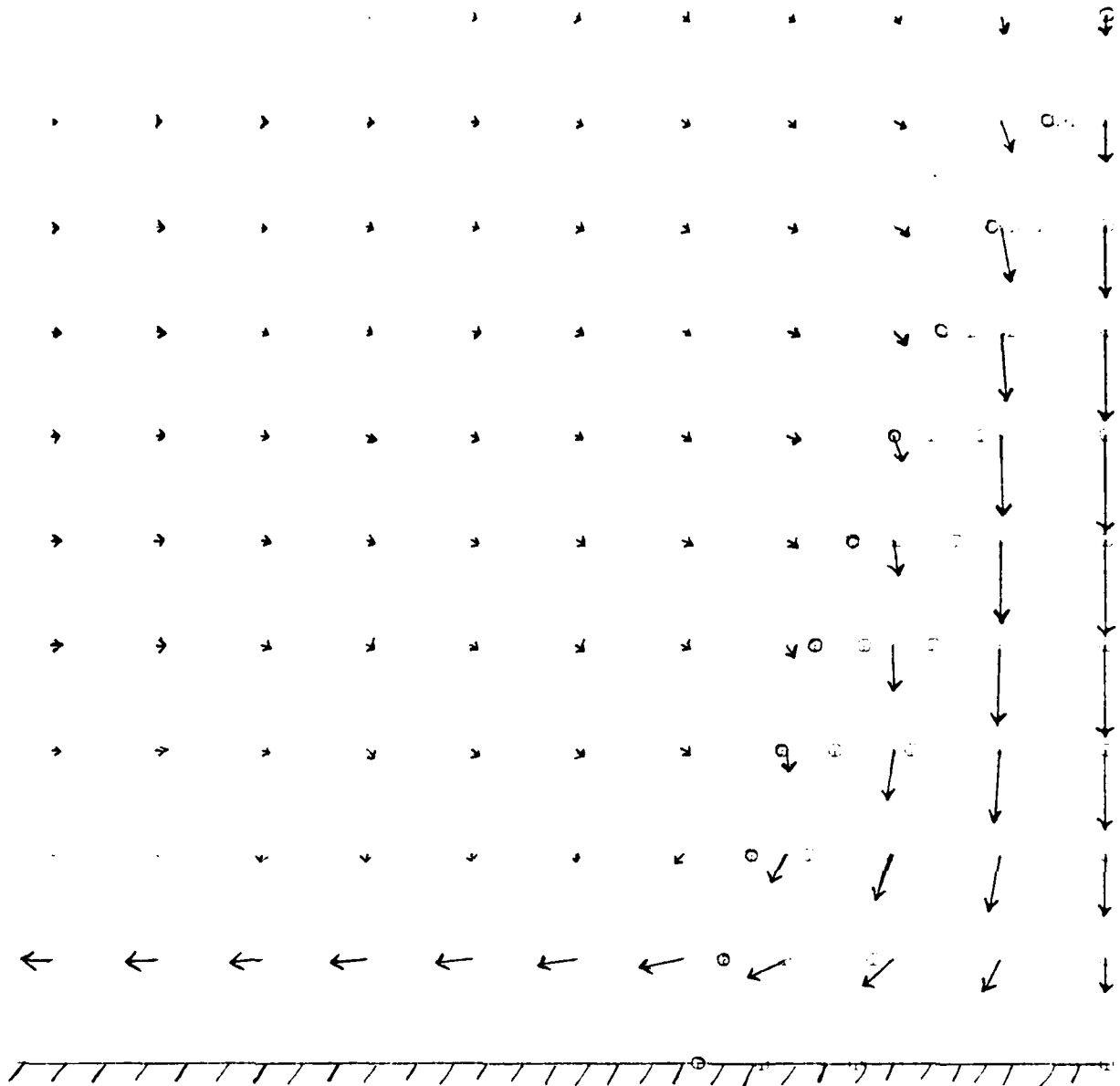
FIGURE 9 FLOW FIELD AND PARTICLE TRAJECTORIES



← CORRESPONDS TO A GAS VELOCITY TO
INJECTION VELOCITY RATIO OF 10 PERCENT
○○○○ REPRESENTS PARTICLE TRAJECTORIES

LEHLEN 21 MM I.D.
NOZZLE DIAMETER 0.40 MM
GASE FLOW OF SPRAY 3000 L.P.P. REF
LIQUID FLOW 21.0 L.T. PER MIN
NOZZLE I.D. 0.40 MM
SPRAY HEIGHT 0.00 M

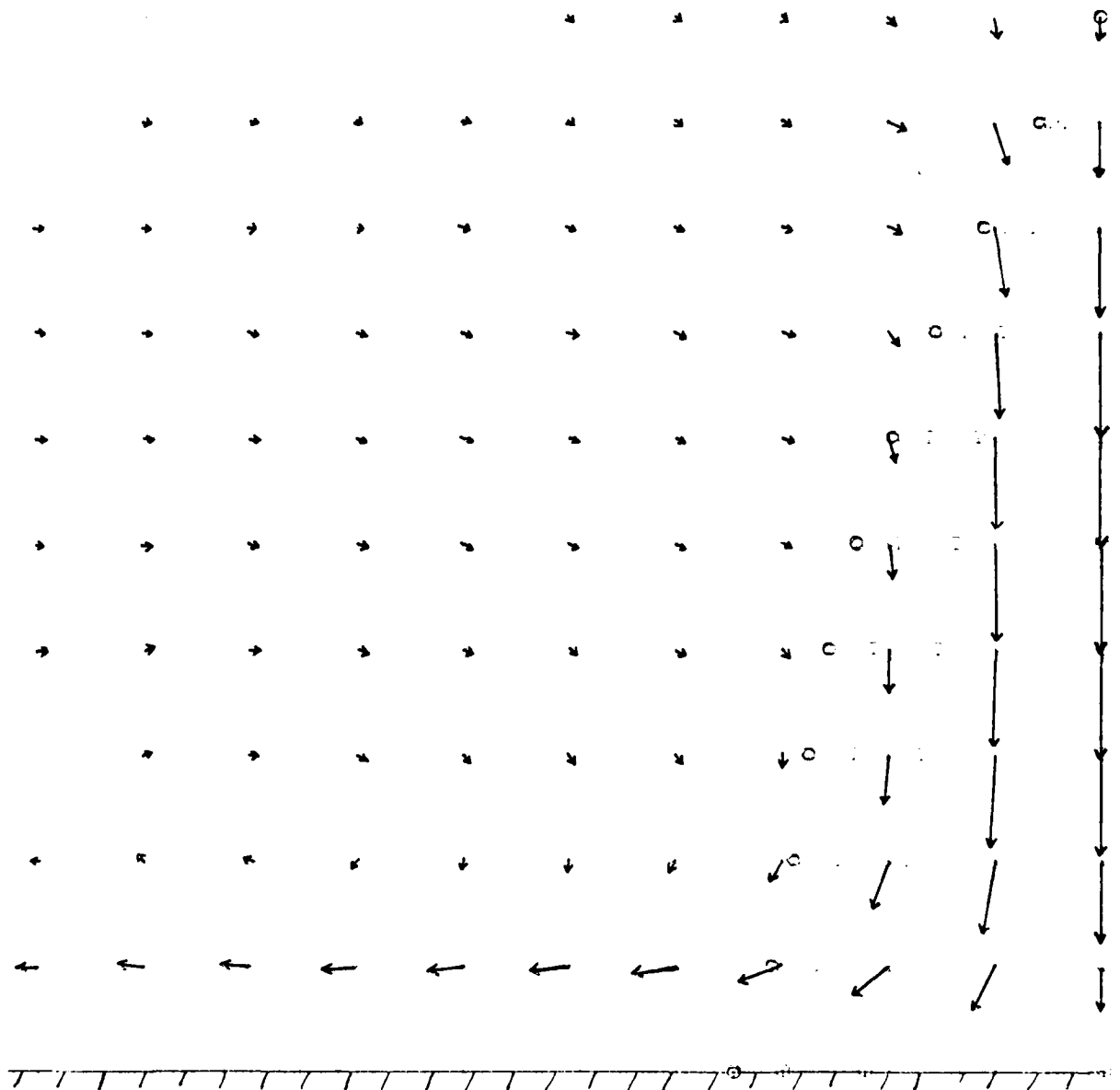
FIGURE 10 FLOW FIELD AND PARTICLE TRAJECTORIES



← CORRESPONDING TO A G.A. VELOCITY OF
INJECTION VELOCITY RATIO OF 0.5. FREQUENT
O O O O REPRESENTS PARTICLE TRAJECTORIES

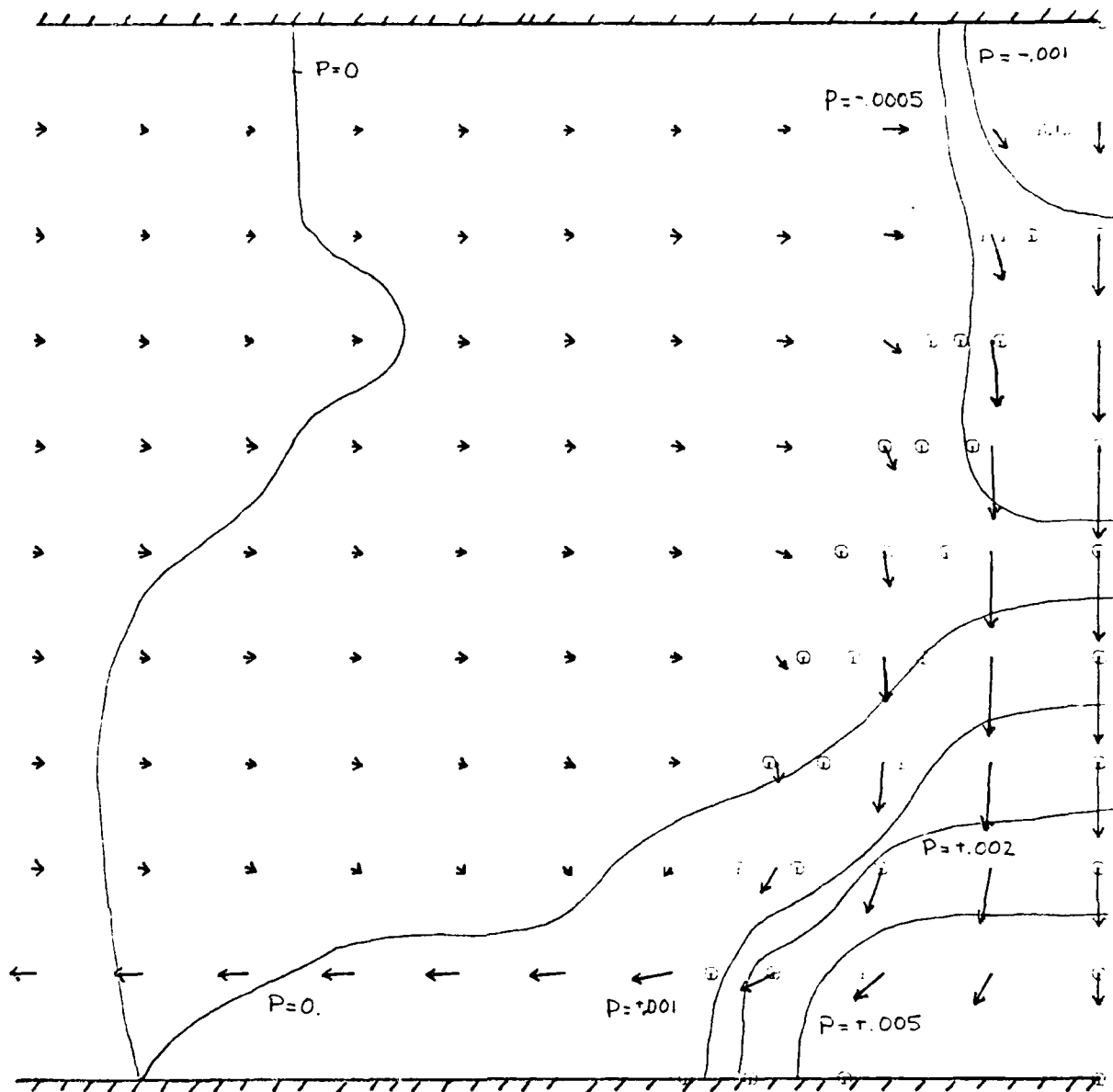
LECHLER 021 NOZZLE
NOZZLE DIAMETER 4.4 MM
HALF ANGLE OF SPRAY 30.0 DEGREE
LIQUID VOLUME FLOW 1.5 LITER PER MIN
DROPLET SIZE 1.00 MM
SPRAY HEIGHT 1.0 M

FIGURE 11. FLOW FIELD OF A PARTICLE TRAJECTORY



← CORRESPONDS TO A GAS VELOCITY OF
INJECTION VELOCITY RATIO OF 1.0 PER CM
o o o o REPRESENTS PARTICLE TRAJECTORIES

GEOMETRY: 2. INCHES
D. 1.00 INCHES
WALL ANGLE 15 DEGREES
FLOW RATE 1.00 LITER PER MIN
INLET SIZE 0.40 MM
WALL HEIGHT 1.00 MM



← CORRESPOND TO A GA VELOCITY TO
 INJECTION VELOCITY RATIO OF 10 PER CENT
 o o o o REPRESENT PARTICLE TRAJECTORIES
 $P = \text{PRESSURE} / \rho U_0^2$

LEINER 21 IN. DIA.
 NOZZLE 1.14 IN. DIA.
 HALF ANGLE OF SPRAY 30 DEGREES
 LIQUID VELOCITY 100 FT PER MIN
 DROPLET SIZE 100 MICRONS
 SPRAY HEIGHT 1.00 IN

d_o mm	Q_w lt/min	ΔP_N kPa	D mm	θ_{max}
4.4	6.6	34.3	1.05	30°
	13.3	176.5	.61	30°
	21.1	617.8	.40	30°

Table 1. Properties of Lechler SZ1 Nozzle.

APPENDIX - LISTING OF SPRAY COMPUTER PROGRAM

MAIN Program	p. 40
Subroutine COEFF	p. 49
Subroutine PSOURC	p. 55
Subroutine SOR	p. 60
Subroutine GASVEL	p. 65
Subroutine PARTCL	p. 68
Input FILE	p. 74
Output FILE	p. 75


```

13100 C SET SWITCH FOR INITIAL SOLUTION (0=START SOLU FROM AIR AT REST)
13200 C (1=INITIAL SOLUTION PROVIDED IN FILE 19)
13300 C READ(20,219)INITIAL
13400 C 219 FORMAT(//IX,11)
13500 C *****
13600 C SET UP GRID
13700 C *****
13800 C SET NUMBER OF PRESSURE NODES IN RADIAL DIRECTION
13900 C SET NUMBER OF PRESSURE NODES IN AXIAL DIRECTION
14000 C READ(20,209)NX,NY
14100 C 209 FORMAT(//IX,2(I2,2X))
14200 C WRITE(6,210)NX,NY
14300 C 210 FORMAT(IX,12,2X,'N1=',12)
14400 C CALCULATE PRESSURE NODE LOCATIONS
14500 C DELX=RL/FLUAT(NX-1)
14600 C DELY=ZL/FLUAT(NY-1)
14700 C DO 5 I=1,NX
14800 C X(I)=FLUAT(I-1)*DELX
14900 C CONTINUE
15000 C DO 6 J=1,NY
15100 C Y(J)=FLUAT(J-1)*DELY
15200 C CONTINUE
15300 C *****
15400 C SET OF SUBROUTINE INPUTS FOR SOLUTION OF POISSON EQUATION
15500 C *****
15600 C SPECIFY TYPE OF BOUNDARY CONDITION ON EACH BOUNDARY
15700 C 0=CIRCULAR BC
15800 C 1=RECTANG BC
15900 C 2=X BOUNDARY OR X=NRADIUS BOUNDARY
16000 C 3=Y BOUNDARY OR Y=NRADIUS BOUNDARY
16100 C 4=X BOUNDARY OR X=0 BOUNDARY
16200 C 5=Y BOUNDARY OR Y=0 BOUNDARY
16300 C 6=X BOUNDARY OR Y=NRADIUS BOUNDARY
16400 C 7=Y BOUNDARY OR X=NRADIUS BOUNDARY
16500 C 8=X BOUNDARY OR X=0 BOUNDARY
16600 C 9=Y BOUNDARY OR Y=0 BOUNDARY
16700 C 10=X BOUNDARY OR Y=NRADIUS BOUNDARY
16800 C 11=Y BOUNDARY OR X=NRADIUS BOUNDARY
16900 C 12=X BOUNDARY OR X=0 BOUNDARY
17000 C 13=Y BOUNDARY OR Y=0 BOUNDARY

```

```

17100 C J=1 BOUNDARY OF Y=0 BOUNDARY
17200 C I=1 J=1
17300 C PRESSURE SOLUTION AT BOUNDARIES
17400 C X=0 AND X=L BOUNDARIES
17500 C NORMAL DERIVATIVE OF PRESSURE EQUAL ZERO
17600 C DO 20 J=1,NY
17700 C   PBC(J)=0.
17800 C   PBC(L)=0.
17900 C CONTINUE
18000 C NORMAL DERIVATIVE OF PRESSURE EQUALS MINUS THE
18100 C PRESSURE GRADIENT AT Y=AXING BOUNDARY
18200 C DO 21 I=1,NX
18300 C   ABC(I)=0.
18400 C   CBC(I)=0.
18500 C CONTINUE
18600 C 21 Y=0 AND Y=L BOUNDARIES
18700 C DO 30 I=1,NX
18800 C   PRESS(I,1)=0.
18900 C   PRESS(I,NY)=0.
19000 C CONTINUE
19100 C 30
19200 C
19300 C CALCULATE INITIAL GUESSED PRESSURE AT INTERIOR POINTS
19400 C DO 10 I=1,NX-1
19500 C DO 10 J=1,NY
19600 C   PRESS(I,J)=0.
19700 C CONTINUE
19800 C 10 SET MAXIMUM NUMBER OF ITERATIONS FOR SUB ROUTINE
19900 C ITERM=999
20000 C SET INITIAL OVERRELAXATION FACTOR
20100 C OMEGA=1.5
20200 C *****
20300 C SET UP SUBROUTINE INPUTS FOR SOLUTION OF VELOCITY FIELD
20400 C *****
20500 C GUESSED SOLUTION FOR VELOCITY
20600 C IF ITERM=0 INITIAL FLOW FIELD SET TO ZERO
20700 C IF ITERM=1 INITIAL FLOW FIELD FROM FILE 19
20800 C IF ITERM=2 INITIAL FLOW FIELD FROM FILE 19
20900 C DO 9 J=1,NY+1
21000 C DO 9 I=1,NX
21100 C   VZ(I,J)=0.
21200 C CONTINUE
21300 C 9
21400 C

```



```

21500 DO 19 I=1,NX+1
21600 DO 19 J=1,NY
21700 VR(I,J)=0.
21800 C CONTINUE
21900 C 19 CALCULATE BOUNDARY VALUES OF VELOCITY
22000 DO 7 I=1,NX
22100 VZ(I,1)=0.
22200 VZ(I,NY)=VZ(I,NY+1)
22300 C CONTINUE
22400 DO 8 I=1,NX+1
22500 VR(I,1)=0.
22600 VR(I,NY)=0.
22700 C CONTINUE
22800 GO TO 52
22900 C 10 INITIAL SOLUTION READ FROM FILE 19 IF 1-PSOL=1
23000 91 READ(19,93)
23100 93 FORMAT(////////)
23200 DO 40 I=1,NM2PAK
23300 401 READ(19,407)
23400 407 FORMAT(IY)
23500 DO 45 J=1,NY
23600 DO 46 I=1,NX
23700 READ(19,304)X1,Y1,PRESSE(I,J),X2,Y2,VZ(I,J),
23800 1X3,Y3,VR(I,J)
23900 C CONTINUE
24000 READ(19,305)X1,Y1,VR(NX+1,J)
24100 45 CONTINUE
24200 DO 47 I=1,NX
24300 READ(19,306)X1,Y1,VZ(I,NY+1)
24400 47 CONTINUE
24500 92 CONTINUE
24600 C *****
24700 C ITERATE FOR THE SOLUTION OF THE PRESSURE AND VELOCITY FIELDS
24800 C *****
24900 C CALCULATE COEFFICIENTS OF LEFT HAND SIDE OF PDE
25000 C SAME FOR ALL TIME
25100 C CALL COEFF(NX,NY,PT50F)
25200 C SET SOURCE TERMS EQUAL TO ZERO
25300 C DO 82 I=1,NX
25400
25500
25600
25700
25800

```

```

25900      DO 82 J=1,NY
26000      FX(I,J)=0.
26100      FZ(I,J)=0.
26200      CONTINUE
26300      C  CALCULATE INITIAL SOURCE TERMS
26400      DO 81 I=1,NXPAP
26500      WRITE(28,307)
26600      CALL PARTICLE(R,Z,1.0,0Z,DF(I),TOL,FAO(I),FRACO(I))
26700      DO 84 J=1,NY+2
26800      WRITE(28,308)P(J),Z(O),T(J),UF(J),0Z(J)
26900      CONTINUE
27000      C  CONTINUE
27100      DO 138 J=1,NY
27200      WRITE(28,351)P(1,I),P(2,I),P(3,I),P(4,I),P(5,I)
27300      WRITE(28,351)PZ(1,I),PZ(2,I),PZ(3,I),PZ(4,I),PZ(5,I)
27400      351 FORMAT(1X,5F12.5,2X)
27500      CONTINUE
27600      DO 52 IITER=1,60011
27700
27800      C  UPDATE SOURCE TERMS FOR PRESSURE EQUATION USING NEW
27900      C  VELOCITY
28000      CALL PSOURCE(OA,NY,PRESSC)
28100      C  UPDATE PARTICLE FIELD AND PARTICLE SOURCE TERMS
28200      C  EVERY TENH ITERATION
28300      L=L+1
28400      IF(L.LI.10)GO TO 234
28500      L=0
28600      C  SET SOURCE TERMS EQUAL TO ZERO
28700      DO 83 J=1,NY
28800      DO 83 J=1,NY
28900      FX(I,J)=0.
29000      FZ(I,J)=0.
29100      CONTINUE
29200      C  RECALCULATE SOURCE TERMS
29300      DO 85 I=1,NXPAP
29400      CALL PARTICLE(R,Z,1.0,0Z,DF(I),TOL,FAO(I),FRACO(I))
29500      CONTINUE
29600      C
29700

```

```

29800 C ITERATE FOR NEW PRESSURE FIELD USING SUB ROUTINE
29900 C CALL SUB(PRESSR,ITF,DOSEGA,IX,IY,ITRMAX)
30000 C
30100 C OBTAIN NEW VELOCITY FIELD
30200 C CALL GASVEL(IX,IY,VZD,VNLD,PRESSR)
30300 C
30400 C STORE NEW VELOCITY FIELD AND CALCULATE CAUCHY RESIDUAL
30500 C VZDR=0.
30600 C SOLUOR=0.
30700 C DO 29 I=1,NX+1
30800 C DO 29 J=1,NY
30900 C VZDR=VZDR+(VZD(I,J)-VZ(I,J))*Z
31000 C SOLUOR=SOLUOR+VZD(I,J)**2
31100 C VZ(I,J)=VZD(I,J)
31200 C CONTINUE
31300 C DO 28 J=1,NY+1
31400 C DO 28 I=1,NX
31500 C VZDR=VZDR+(VZD(I,J)-VZ(I,J))*Z
31600 C SOLUOR=SOLUOR+VZD(I,J)**2
31700 C VZ(I,J)=VZD(I,J)
31800 C CONTINUE
31900 C VZDR=VZDR/(VZDR/SOLUOR)
32000 C IF SOLUTION STARTS TO BLUR UP STOP PROGRAM
32100 C IF(SOLUOR/FLOAT(NX*NY).GT.100.)STOP
32200 C RAD=NX/2+1
32300 C RTH=NY/2+1
32400 C IF(C.EQ.0)WRITE(6,53)ITF1,VZDR,VZ(NX,NY),VZ(1,NY),
32500 C 1PRESSR(NX,NY),VZ(2,NY),VZ(2,NY),PRESSR(2,NY)
32600 C 53 FORMAT(1X,I4,2X,E12.6,6(2X,F10.5))
32700 C DO 51 I=1,NX+1
32800 C DO 51 J=1,NY+1
32900 C WRITE(30,202)X(I),Y(J),PRESSR(I,J),VZ(I,J),VZ(I,J)
33000 C 51 CONTINUE
33100 C 52 CONTINUE
33200 C *****
33300 C OBTAIN SOLUTION WITH PRESSURE AND VELOCITY FIELDS
33400 C AND PARTICLE TRAJECTORIES
33500 C *****
33600 C *****
33700 C *****
33800 C *****
33900 C *****
34000 C *****
34100 C *****
34200 C *****
34300 C *****
34400 C *****
34500 C *****
34600 C *****

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38100
38200

303 FORMAT(1X,2X,'POSITION',4X,'POSITION',16X,
1'POSITION',4X,'POSITION',15X,'POSITION',4X,'POSITION')
DO 35 J=1,N1
DO 36 I=1,NX
XIH=X(I)-DELX/2.
YOH=Y(J)-DELY/2.
WRITE(30,304)X(I),Y(J),PRESSR(I,J),X(I),YOH,VZ(I,J)
1,XIH,Y(J),VR(I,J)
36 CONTINUE
304 FORMAT(1X,5(F10.5,2X))
XIH=X(NX)+DELX/2.
WRITE(30,305)XIH,Y(J),VR(NX+1,J)
35 CONTINUE
305 FORMAT(1X,72X,3(F10.5,2X))
YOH=Y(NY)+DELY/2.
DO 37 I=1,NX
WRITE(30,306)X(I),YOH,VZ(I,J)
37 CONTINUE
306 FORMAT(1X,36X,3(F10.5,2X))
WRITE(30,307)
309 FORMAT(//1X,'PARTICLE TRAJECTORIES'//)
DO 310 J=1,NBPAN
WRITE(30,311)X(J),THETA0(J),FRAC0(J)
311 FORMAT(1X,'PARTICLE TRAJECTORY FOR DP= ',F10.5,2X,'THETA0= ',
1F10.5,2X,'VOLUME FLOW FRACTION= ',F10.5)
WRITE(30,307)
307 FORMAT(1X,' RADIUS ',2X,'AXIAL DIS',2X,' LINE ',
1X,'RADIAL VEL',2X,'AXIAL VEL')
CALL PARTICLE(Z,V,GR(J),THETA0(J),FRAC0(J))
DO 38 I=1,N1+2-1
WRITE(30,306)X(I),Z(I),I(I),VR(I),VZ(I)
38 CONTINUE
310 CONTINUE
308 FORMAT(1X,5(F10.5,2X))
STOP
END

```

COEFF SUBROUTINE

```

100 SUBROUTINE COEFF(COAX,COY,GUESS)
200 DIMENSION CDE(50,50),CDEW(50,50),CSE(50,50),CSW(50,50)
300 DIMENSION CW(50,50),CW(50,50),C(50,50),CS(50,50)
400 DIMENSION CE(50,50),CE(50,50),F(50,50)
500 DIMENSION AC(50),F(50),GROSS(50,50)
600 DIMENSION ABC(50),ABC(50),CBC(50),CBC(50)
700 DIMENSION FODD(50,50)
800 COMMON CDE,CDEW,CSE,CSEW,C(50,50),C(50,50),CP,F
900 COMMON /BOUNDARY/ABC,BBC,CBC,CBC,ACROSS,BCROSS,CROSS,DCROSS
1000 COMMON /BOUNDARY2/ LEFT,RIGHT,ITOP,BOTTOM
1100 COMMON /BOUNDARY3/ FODDLE
1200 COMMON /DELT/ DELT,DELT,DELT
1300 COMMON /COORD/ X,Y
1400 C*****
1500 C THIS SUBROUTINE CALCULATES THE TOP LEFT HAND SIDE OF THE
1600 C DISCRETIZED PDE FOR THE POISSON TYPE EQUATION FOR
1700 C THE PRESSURE
1800 C
1900 C**INPUT TO THIS SUBPROGRAM IS AS FOLLOWS:
2000 C
2100 C "COAX" AND "COY" ARE THE ORDER OF PRESSURE NODES IN THE
2200 C X AND Y DIRECTIONS
2300 C
2400 C X=RADIAL DIRECTION, Y=AXIAL DIRECTION
2500 C
2600 C "GUESS" IS THE GUESSED SOLUTION VECTOR FOR USE WITH
2700 C ADAPTIVE COEFFICIENTS (NOT USED HERE)
2800 C
2900 C**INPUT FROM COMMON BLOCK
3000 C
3100 C THE "BOUNDARY" COMMON BLOCK CONTAINS THE INFORMATION FOR THE
3200 C BOUNDARY CONDITIONS AT THE FOUR BOUNDARIES. THE
3300 C FIRST FOUR VECTORS CONTAIN THE COEFFICIENTS OF THE LOGICAL
3400 C DERIVATIVES. THE LAST FOUR ENTRIES DEAL WITH THE CROSS
3500 C DERIVATIVES AT THE FOUR CORNERS. SEE WRITE-UP FOR MORE
3600 C INFORMATION
3700 C
3800 C THE "BOUNDARY2" COMMON BLOCK CONTAINS THE SWITCHES FOR THE
3900 C TYPE OF BOUNDARY CONDITION AT THE FOUR BOUNDARIES.
4000 C =1 FOR PERMANENT BOUNDARY CONDITIONS
4100 C =0 FOR PERIODIC BOUNDARY CONDITIONS

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```

8300      CS(1,0)=CSE(1,0)
8400      CC1=1./DELY**2
8500      CA=1./DELY**2
8600      CCE=0.
8700      CEX=(1./X(1))/(2.*DELY)
8800      CC1(0)=CC1+CCY
8900      CS(1,0)=CC1-CCY
9000      CE(1,0)=CA+CEX
9100      CW(1,0)=CA-CWA
9200      CC1(0)=-2.*CA-2.*CC1
9300      FROD(1,0)=0.
9400      CCE=0.
9500
9600      *****
9700      *****MODIFY COEFFICIENTS OF INTERIOR POINTS NEXT TO BOUNDARY
9800      *****FOR "FURCA" CONDITIONS*****
9900      *****
10000
10100
10200
10300
10400
10500      CP(2,2)=CP(2,2)+CW(2,2)*FLOAT(ILFFT)+CS(2,2)
10600      1*FLOAT(1BOLTM)+CSE(2,2)*FLOAT(ILEF1+1BOLTM)
10700      CC(2,2)=CC(2,2)+CW(2,2)*FLOAT(ILEF1)
10800      CE(2,2)=CE(2,2)+CSE(2,2)*FLOAT(1BOLTM)
10900      FROD(2,2)=-((-CW(2,2)*DELA*CBC(2)-CWA(2,2)*DELY*CBC(3))
11000      1*FLOAT(ILEF1)+(-CS(2,2)*DELY*CBC(2)-CSE(2,2)*DELY*CBC(3))*
11100      2*FLOAT(1BOLTM)+CWA(2,2)*(-DELA*CBC(2)-DELY*CBC(2)+DELY*DELY*
11200      3*CCF(3,3))*FLOAT(ILEF1+1BOLTM))
11300      CS(2,2)=CW(2,2)*FLOAT(1-ILEF1+1BOLTM)/2)
11400      CC(2,2)=CC(2,2)*FLOAT(1-ILEF1)
11500      CE(2,2)=CW(2,2)*FLOAT(1-ILEF1)
11600      CS(2,2)=CS(2,2)*FLOAT(1-1BOLTM)
11700      CSE(2,2)=CSE(2,2)*FLOAT(1-1BOLTM)
11800
11900
12000
12100
12200      *****MODIFY COEFFICIENTS NEXT TO LEFT BOUNDARY FOR "FURCA"
12300      *****CONDITIONS ON LEFT SIDE*****
12400
12500      DO 10 J=3,NY-2
12600      CC(2,0)=CC(2,0)+CW(2,0)*FLOAT(ILEF1)
12700      CE(2,0)=CP(2,0)+CW(2,0)*FLOAT(ILEF1)
12800      CS(2,0)=CS(2,0)+CW(2,0)*FLOAT(ILEF1)
12900      FROD(2,0)=-(-CW(2,0)*DELA*CBC(J+1)-CWA(2,0)*DELY*CBC(J))
13000      1-CWA(2,0)*DELY*CBC(J-1))*FLOAT(ILEF1)
13100      CCW(2,0)=CW(2,0)*FLOAT(1-ILEF1)

```



```

17100 CF(CX1,NY1)=CF(CX1,NY1)+CF(CX1,NY1)*FLOAT(1-RIGHT)
17200 1+CX(CX1,NY1)*FLOAT(1TOP)+CSE(CX1,NY1)*FLOAT(1TOP*1-RIGHT)
17300 CW(CX1,NY1)=CW(CX1,NY1)+CW(CX1,NY1)*FLOAT(1TOP)
17400 ICROSS=1-RIGHT*1TOP
17500 FORDJAD(CX1,NY1)=-((-CSE(CX1,NY1)*DELA*DEC(NY-1)
17600 1-CSE(CX1,NY1)*DELY*DEC(NX-2)))*FLOAT(1-RIGHT)+(-CX(CX1,NY1)*
17700 2*DELY*ABC(NY-1)-CW(CX1,NY1)*DELY*ABC(NY-2))*FLOAT(1TOP)+
17800 3(CW(CX1,NY1)*(-CDELA*DEC(NY1)-DELY*ABC(NY1)+DELY*DELA*
17900 4*ABC(NY5)))*FLOAT(1CROSS))
18000 CW(CX1,NY1)=CW(CX1,NY1)+FLOAT(1-1TOP)
18100 CSE(CX1,NY1)=CSE(CX1,NY1)*FLOAT(1-1TOP)
18200 CDE(CX1,NY1)=CDE(CX1,NY1)*FLOAT(1-1TOP)
18300 CDE(CX1,NY1)=CDE(CX1,NY1)*FLOAT(1-1TOP)/2)
18400 CF(CX1,NY1)=CF(CX1,NY1)*FLOAT(1-1-RIGHT)
18500 CSE(CX1,NY1)=CSE(CX1,NY1)*FLOAT(1-1-RIGHT)
18600
18700
18800
18900
19000
19100
19200
19300
19400
19500
19600
19700
19800
19900
20000
20100
20200
20300
20400

```

MODIFY COEFFICIENTS NEXT TO RIGHT BOUNDARY FOR FLOWAGE
CONDITIONS ON RIGHT SIDE

```

DO 30 J=3,NY-2
CX(NX-1,J)=CX(NX-1,J)+CF(NX-1,J)*FLOAT(1-RIGHT)
CP(NX-1,J)=CP(NX-1,J)+CSE(NX-1,J)*FLOAT(1-RIGHT)
CS(NX-1,J)=CS(NX-1,J)+CSE(NX-1,J)*FLOAT(1-RIGHT)
FORDJAD(NX-1,J)=-(-CSE(NX-1,J)*DELA*DEC(J+1)-
1CE(NX-1,J)*DELA*DEC(J)-CSE(NX-1,J)*DELA*DEC(J-1))*
2FLOAT(1-RIGHT)
CSE(NX-1,J)=CSE(NX-1,J)*FLOAT(1-1-RIGHT)
CE(NX-1,J)=CE(NX-1,J)*FLOAT(1-1-RIGHT)
CDE(NX-1,J)=CDE(NX-1,J)*FLOAT(1-1-RIGHT)
CDELI=0

```

MODIFY COEFFICIENTS AT RIGHT BOUNDARY CORNER FOR FLOWAGE
CONDITIONS ON OUTLINE AND/OR FLIGHT SLIPS

30

CC
CC
CC
CC

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PSOURC SUBROUTINE

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100  SUBROUTINE PSOURC(CX, CY, GUTS)
200  DIMENSION CUE(50,50), CUE(50,50), CSE(50,50), CSA(50,50)
300  DIMENSION CW(50,50), CW(50,50), CS(50,50)
400  DIMENSION CE(50,50), CP(50,50), P(50,50), GUES(50,50)
500  DIMENSION VR(50,50), VZ(50,50), X(50), Y(50), PRG(50,50)
600  DIMENSION ABC(50), BEC(50), CEC(50), DSC(50)
700  DIMENSION PR(50,50), FZ(50,50)
800  COMMON CUE, CW, CSE, CSW, CS, CE, CX, CY, P
900  COMMON ZDEL, DELX, DELY, DELT
1000  COMMON ZAIR, V, VZ, VR
1100  COMMON ZSG, ZAF, Y3, PRG
1200  COMMON ZCUEU, X, Y
1300  COMMON ZKEY, ZDS, FE
1400  COMMON ZSOURCE, FR, FZ
1500  C*****
1600  C THIS SUBROUTINE CALCULATES THE RIGHT HAND SIDE OF THE
1700  C DISCRETEIZED PDE FOR THE POLISSON TYPE EQUATION. FOR

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1800      THE PRESSURE
1900
2000      ***INPUT TO THIS SUBPROGRAM IS AS FOLLOWS:
2100
2200      "IX" AND "IY" ARE THE NUMBER OF PRESSURE NODES IN THE
2300      X AND Y DIRECTIONS
2400
2500      X=RADIAL DIRECTION, Y=AXIAL DIRECTION
2600
2700      "GUESS" IS THE GUESSED SOLUTION VECTOR FOR USE WITH
2800      NONLINEAR COEFFICIENTS
2900
3000      THE "DEL" COMMON BLOCK CONTAINS THE RADIAL AND AXIAL
3100      INCREMENTAL DELTAS AND "DELA" AND "DELY", AND THE
3200      INCREMENTAL TIME "DELT"
3300
3400      THE "AIR V" COMMON BLOCK CONTAINS THE RADIAL AND AXIAL
3500      COORDINATES X AND Y OF THE PRESSURE NODES
3600
3700      THE "BOUNDARY3" COMMON BLOCK CONTAINS THE CONTRIBUTIONS
3800      TO THE RIGHT HAND SIDE OF THE PLE DUE TO "WALL" AND
3900      BOUNDARY CONDITIONS
4000
4100      THE "REYNOLDS" COMMON BLOCK CONTAINS THE REYNOLDS NUMBER
4200      OF NONDIMENSIONALIZATION
4300
4400      THE "SOURCE" COMMON BLOCK CONTAINS THE SOURCE TERMS OF THE
4500      MOMENTUM EQUATIONS
4600
4700      ***ALSO REQUIRED AS INPUT FOR THIS SUBPROGRAM ARE THE SET OF
4800      FUNCTION SUBPROGRAMS WHICH CALCULATE THE SQUARE OF THE
4900      VELOCITIES, THE CROSS MULTIPLICATION OF THE VELOCITIES,
5000      AND THE DILATION TERM. THESE ARE GIVEN AFTER THIS
5100      SUBPROGRAM.
5200
5300      ***OUTPUT FROM THE COMMON BLOCK
5400
5500      THE COMMON BLOCK OUT RATED CONTAINS THE COEFFICIENTS OF THE
5600      DISCRETIZED PDE AT EACH POINT IN THE COMPUTATIONAL MESH.
5700      AS A FUNCTION OF THE MOLECULE'S POSITION IN THE MESH. ONE
5800      OF THESE COEFFICIENTS IS CALCULATED IN THIS SUBROUTINE.

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14300
14400
14500
14600
14700
14800
14900

10  CONTINUE
    MODIFY RIGHT HAND SIDE AT LEFT FOR CORNER FOR WEEDAW
    CONDITIONS ON TOP AND/OR LEFT SIDES
        F(2,XY-1)=F(2,XY-1)+FBOUND(2,XY-1)
    MODIFY RIGHT HAND SIDE NEXT TO TOP BOUNDARY FOR WEEDAW
    CONDITIONS ON TOP SIDE
        DO 20 I=3,IX-2
            F(1,XY-1)=F(1,XY-1)+FBOUND(1,XY-1)
        20  CONTINUE
    MODIFY RIGHT HAND SIDE AT RIGHT FOR CORNER FOR WEEDAW
    CONDITIONS ON TOP AND/OR RIGHT SIDES
        IX=IX-1
        IY=IY-1
        F(IX,IY)=F(IX,IY)+FBOUND(IX,IY)
    MODIFY RIGHT HAND SIDE NEXT TO RIGHT BOUNDARY FOR WEEDAW
    CONDITIONS ON RIGHT SIDE
        DO 30 J=3,IY-2
            F(IX-1,J)=F(IX-1,J)+FBOUND(IX-1,J)
        30  CONTINUE
    MODIFY RIGHT HAND SIDE AT RIGHT BOTTOM CORNER FOR WEEDAW
    CONDITIONS ON BOTTOM AND/OR RIGHT SIDES
        F(IX-1,2)=F(IX-1,2)+FBOUND(IX-1,2)
    MODIFY RIGHT HAND SIDE NEXT TO BOTTOM BOUNDARY FOR WEEDAW
    CONDITIONS ON BOTTOM SIDE
        DO 40 I=3,IX-2
            F(1,2)=F(1,2)+FBOUND(1,2)
        40  CONTINUE
        RETURN
    END

```



```

100 SUBROUTINE SOL(SOLN,ITER,MODRCA,IX,MY,UMAXX)
200 PLEASION SOLN(50,50),GUESS(50,50)
300 PLEASION C0(50,50),C0X(50,50),C0Y(50,50),CSX(50,50),CSY(50,50)
400 PLEASION C1(50,50),C1X(50,50),C1Y(50,50),C2(50,50),C2X(50,50)
500 PLEASION CP(50,50),CPX(50,50)
600 PLEASION AN(50),ANC(50),BC(50),BNC(50),BNC(50)
700 C0=0.0 C1=0.0 CSX=0.0 CSY=0.0 C0X=0.0 C0Y=0.0 CP=0.0
800 C0=0.0 /BOUNDARY/ ABC,BNC,BC,BNC,ACROSS,BCROSS,DCROSS,DCROSS
900 C0=0.0 /BOUNDARY/ LEFT,RIGHT,TOP,BOTTOM
1000 C0=0.0 /BET/ BETA,ONLY,BET
1100 *****
1200 THIS PROGRAM USES THE SUCCESSIVE-OVER-RELAXATION SCHEME TO
1300 ITERATE FOR THE ELLIPTIC EQUATION SOLUTION
1400 *****
1500 C++INPUT TO THIS SUBROUTINE IS AS FOLLOWS:
1600
1700 "SOLN" HOLDS THE GUESSED SOLUTION VECTOR INITIALLY
1800 AFTER EACH ITERATION "SOLN" HOLDS THE UPDATED SOLUTION
1900 AND "GUESS" HOLDS THE OLD SOLUTION.
2000
2100 DETAILS ON THE GUESSED SOLUTION.
2200 THE GUESSED SOLUTION CAN BE CHOSEN AT DIFFERENT POINTS AS THE
2300 USER DESIRES IT. AT THE BOUNDARIES THE GUESSED SOLUTION MUST
2400 COMPLY THE VALUES OF THE SOLUTION AT THE BOUNDARIES WHERE THE
2500 DIFFERENT CONDITIONS EXIST, INCLUDING CORNER POINTS. ALONG THE
2600 BOUNDARIES WHERE THE PROBABLE CONDITIONS EXIST THE USER MAY
2700 SUPPLY GUESSED VALUES THROUGH THESE ARE NOT USED IN THE
2800 CALCULATION.
2900
3000 "MODRCA" CONTAINS THE FIRST GUESSED VALUE OF THE RELAXATION
3100 FACTOR, UPDATED AT SUCCESSIVE ITERATIONS BY USING THE RATIO
3200 OF THE RESIDUALS AT SUCCESSIVE ITERATIONS.
3300
3400 "IX" AND "MY" ARE THE NUMBER OF DISCRETIZED POINTS IN
3500 THE X AND Y DIRECTIONS.
3600
3700 "ITERMAX" IS THE MAXIMUM NUMBER OF ITERATIONS TO BE ALLOWED.
3800 IF THE SOLUTION DOES NOT CONVERGE BY ITERMAX ITERATIONS A
3900 MESSAGE IS PRINTED OUT AT THE SCREEN
4000 *****

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4100 C ***** THROUGH THE CORNER POINTS ARE AS FOLLOWS:
4200 C
4300 C THE CORNER BLOCK REF VECTOR CONTAINS THE COEFFICIENTS OF THE
4400 C DISCRETIZED FOR AT EACH POINT IN THE COMPUTATIONAL ELEMENT
4500 C FOR EACH COMPUTATIONAL POINT. THIS INFORMATION IS
4600 C CALCULATED IN THE SUBROUTINE CORN.
4700 C
4800 C THE "SUBCORN" CORNER BLOCK CONTAINS THE INFORMATION FOR THE
4900 C REFERENCE POINTS AT THE FOUR BOUNDARIES. THE
5000 C FIRST FOUR VECTORS CONTAIN THE COEFFICIENTS OF THE NORMAL
5100 C DERIVATIVES. THE LAST FOUR VECTORS DEAL WITH THE CROSS
5200 C DERIVATIVES AT THE FOUR CORNERS. SEE WRITE-UP FOR MORE
5300 C INFORMATION.
5400 C
5500 C THE "BOUNDARY2" CORNER BLOCK CONTAINS THE SWITCHES FOR THE
5600 C TYPE OF BOUNDARY CONDITIONS AT THE FOUR BOUNDARIES
5700 C =1 FOR MICHARD BOUNDARY CONDITIONS
5800 C =2 FOR DIRICHLET BOUNDARY CONDITIONS
5900 C THE BOUNDARY IS DEFINED AS BOUNDARY WITH J=1
6000 C RIGHT BOUNDARY IS DEFINED AS BOUNDARY WITH J=2
6100 C LEFT BOUNDARY IS DEFINED AS BOUNDARY WITH J=3
6200 C
6300 C THE "DEL" CORNER BLOCK CONTAINS THE RADIAL AND AXIAL
6400 C DIFFERENTIAL LENGTHS "DELA" AND "DELT", AND THE
6500 C DIFFERENTIAL TIME "DELT"
6600 C
6700 C ***** OUTPUT OF THE SUBPROGRAM IS AS FOLLOWS:
6800 C
6900 C "SOLN" IS THE SOLUTION VECTOR SOLVED FOR DURING THE ITERATIONS
7000 C IT REPRESENTS THE UPDATED SOLUTION VECTOR DURING THE ITERATIONS
7100 C AND THE FINAL SOLUTION AT CONVERGENCE
7200 C
7300 C "ITER" IS THE NUMBER OF ITERATIONS REQUIRED FOR CONVERGENCE
7400 C
7500 C ***** INPUT DATA FILES
7600 C
7700 C THE VALUES OF THE PERIODAL, THE PERIODAL NORMALIZED BY THE
7800 C SUBSTATION, AND THE RELAXATION FACTOR AT EACH ITERATION ARE
7900 C MULTIPLIED TO FILE FOR031.DAT
8000 C
8100 C *****
8200 C

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8300 C PUT GUESSED SOLUTION INTO SOLUTION VECTOR
8400 DO 5 I=1,NX
8500 DO 5 J=1,NY
8600 GUESS(I,J)=SOLN(I,J)
8700 CONTINUE
8800
8900 C START ITERATION FOR SOLUTION
9000 DO 100 IERR=1,IERRMAX
9100
9200 C DETERMINE SOLN AT INTERIOR POINTS FOR CURRENT SWEEP
9300
9400 I00VEVE=(IERR+1)/2-IERR/2
9500 FOR IERR, 000 SWEEP DIRECTION IS FORWARD, IERR EVEN SWEEP
9600 DIRECTION IS BACKWARD
9700 I00VEVE=0 FOR IERR=EVEN, I00VEVE=1 FOR IERR=ODD
9800 IFACI=0
9900
10000 JFACT=0
10100 IF(I00VEVE.EQ.1) GO TO 1
10200 IFACI=NX+1
10300 JFACT=NY+1
10400
10500 I00VEVE=(-1.)*I00VEVE
10600 DO 10 J=2,NY-1
10700 JC=JFACT+I00VEVE*I
10800 DO 10 I=2,NX-1
10900 IC=IFACT+I00VEVE*I
11000 C PUT OLD SOLUTION INTO GUESS SOLUTION VECTOR AT POINT IC,JC
11100 GUESS(IC,JC)=SOLN(IC,JC)
11200 C CALCULATE NEW SOLUTION AT IC,JC
11300 CCFUS=CE(IC,JC)+SOLN(IC+1,JC)+CW(IC,JC)*SOLN(IC-1,JC)
11400 1+CE(IC,JC)+SOLN(IC,JC+1)+CS(IC,JC)*SOLN(IC,JC-1)
11500 CCFOR=CE(IC,JC)+SOLN(IC,JC)+CW(IC+1,JC)+CS(IC,JC)*SOLN(IC-1,JC+1)
11600 1+CS(IC,JC)+SOLN(IC+1,JC-1)+CSW(IC,JC)*SOLN(IC-1,JC-1)
11700 SOLN(IC,JC)=(1.-I00VEVE)*CCFUS+I00VEVE*CCFOR
11800 1(CCFOR+CCFUS-F(IC,JC))
11900 CONTINUE
12000
12100 C CALCULATE RESIDUAL - QUADRATIC NORM
12200 NORM OF RESIDUAL MAXIMIZED BY NORM OF SOLUTION
12300 TO DETERMINE CONVERGENCE
12400
12500 RESOLD=RESOLD
12600 RESNEW=C.
12700 SOLN=0.

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```

12000 DO 20 J=2,NY-1
12010 CCHGRS=CX(I,J)*SUBS(I+1,J)+CX(I,J)*SUBS(I-1,J)+
12020 1CX(I,J)*SUBS(I,J+1)+CS(I,J)*SUBS(I,J-1)
12030 CCHGRS=CX(I,J)*SUBS(I+1,J+1)+CX(I,J)*SUBS(I-1,J+1)
12040 1+CX(I,J)*SUBS(I+1,J-1)+CS(I,J)*SUBS(I-1,J-1)
12050 SUBRS=CCHGRS+CCHGRS+CX(I,J)*SUBS(I,J)+F(I,J)
12060 RESID=RESID+SUBRS**2
12070 SOLGRS=SOLGR+SUBS(I,J)**2
12080 CONTINUE
12090 RESID=SQRT(RESID)
12100 RESGR=RESGR/SQRT(CCHGRS)
12110 ITERATION FINISHED IF RESIDUAL IS SMALL ENOUGH
12120 IF (RESGR.LT.0.01)GO TO 2
12130 IF (ITER.LT.200) GO TO 100
12140
12150 C FOR ITERATIONS AFTER THE FIRST, RECALCULATE OMEGA BASED ON
12160 C THE CURRENT RESIDUAL AND THE RESIDUAL AT THE PREVIOUS ITERATION
12170 C
12180 C ALAMBDA=RESGR/RESID
12190 WRITE(6,301)ITER,OMEGA,RESGR,RESID
12200 WRITE(6,301)ITER,OMEGA,RESGR,RESID
12210 FURGR(IX,ITERATION,14,IX,OMEGA=1,F/5.5,IX,RESIDUAL=1,
12220 IF(OMEGA,5F,1.0)GO TO 100
12230 IF(OMEGA,5F,1.0)GO TO 100
12240 OMEGA=2.7(1.+SQRT(1.-ALAMBDA))
12250 CONTINUE
12260
12270 SPITE(0,201)ITERAX
12280 FURGR(IX,SOLUTION)NOT CONVERGED AFTER '14,' ITERATIONS')
12290
12300 C DETERMINE SOLUTION AT BOUNDARY FOR DEUMAN: BOUNDARY CONDITIONS
12310 C
12320 C DETERMINE SOLUTION AT BOUNDARY FOR DEUMAN: BC AT LEFT
12330 IF (ITER.LT.0)GO TO 31
12340 DO 41 J=2,NY-1
12350 SUBS(I,J)=SUBS(2,J)-DELX*DBS(J)
12360 CONTINUE
12370
12380 C DETERMINE SOLUTION AT BOUNDARY FOR DEUMAN: BC AT RIGHT
12390 IF (ITER.LT.0)GO TO 32
12400 DO 42 J=2,NY-1
12410 SUBS(IX,J)=SUBS(IX-1,J)-DELX*DBS(J)
12420 CONTINUE
12430
12440 C DETERMINE SOLUTION AT BOUNDARY FOR DEUMAN: BC AT TOP
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17100 32 IF (1,0A-1,0,0)GO TO 33
17200    DO 43 I=2,NX-1
17300      SUB3(1,NY)=SUB3(1,NY-1)-DELTA*ABC(1)
17400 43 CONTINUE
17500 33 DETERMINE SOLUTION AT BOUNDARY FOR NEUMANN BC AT BOTTOM
17600    DO 44 I=2,NX-1
17700      SUB3(1,1)=SUB3(1,2)-DELTA*CBC(1)
17800 44 CONTINUE
17900 34 DETERMINE SOLUTION AT THE LEFT CORNER FOR NEUMANN CONDITION
18000    AT FOR TWO LEFT SIDES
18100 34 IF (1,LEFT+1,0P,EG,0)GO TO 35
18200      SUB3(1,NY)=SUB3(1,NY-1)+SUB3(2,NY)-SUB3(2,NY-1)-
18300      1 DELTA*DELTA*CCROSS
18400 35 DETERMINE SOLUTION AT BOTTOM LEFT CORNER FOR NEUMANN CONDITION
18500    AT BOTTOM AND LEFT SIDES
18600 35 IF (1,LEFT+1,0P,EG,0)GO TO 36
18700      SUB3(1,1)=SUB3(2,1)+SUB3(1,2)-SUB3(2,2)+DELTA*DELTA*CCROSS
18800 36 DETERMINE SOLUTION AT TOP RIGHT CORNER FOR NEUMANN CONDITION
18900    AT TOP AND RIGHT SIDES
19000 36 IF (1,RIGHT+1,0P,EG,0)GO TO 37
19100      SUB3(NX,NY)=SUB3(NX,NY-1)+SUB3(NX-1,NY)-SUB3(NX-1,NY-1)+
19200      1 DELTA*DELTA*CCROSS
19300 37 DETERMINE SOLUTION AT BOTTOM RIGHT CORNER FOR NEUMANN CONDITION
19400    AT BOTTOM AND RIGHT SIDES
19500 37 IF (1,RIGHT+1,0P,EG,0)GO TO 38
19600      SUB3(NX,1)=SUB3(NX,2)+SUB3(NX-1,1)-SUB3(NX-1,2)-
19700      1 DELTA*DELTA*CCROSS
19800 38 RETURN
19900    END
20000

```

GASVEL SUBROUTINE

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100 SUBROUTINE GASVEL(DX, DY, DZ, VR, VP)
200 DIMENSION VZ(50,50), VZa(50,50), VE(50,50), VRa(50,50)
300 DIMENSION X(50), Y(50), P(50,50)
400 DIMENSION PR(50,50), PZ(50,50)
500 COMMON /DEL/ DELX, DELY, DELZ
600 COMMON /COORD/ X, Y
700 COMMON /AIR V/ VZ, VR
800 COMMON /PERIODS/ RE
900 COMMON /SOURCE/ PR, PZ
1000 *****
1100 THIS SUBROUTINE CALCULATES THE UPDATED VELOCITIES
1200 (AXIAL VELOCITY = VZ; RADIAL VELOCITY = VR)
1300 EXPLICITLY FROM THE VELOCITY AND PRESSURE AT THE
1400 PREVIOUS ITERATION. THESE EQUATIONS IN THE AXIAL AND
1500 FORMS OF THE NAVIER-STOKES DIFFERENTIALS ARE USED
1600 RADIAL DIRECTIONS. THE FOLLOWS GEAR THE BOUNDARY IS DONE
1700 (SEE REPORT)
1800 *****
1900 *****
2000 *****
2100 *****
2200 *****
2300 *****
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4400 *****
4500 *****
4600 *****
4700 *****
4800 *****
4900 *****
5000 *****

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INPUT TO THIS SUBROUTINE IS AS FOLLOWS
 "DX" AND "DY" ARE THE NUMBER OF PRESSURE NODES IN
 THE X (RADIAL) AND Y (AXIAL) DIRECTIONS
 "P" IS THE AX BY CY ARRAY OF PRESSURES IN THE FLOW
 FIELD
 INPUT THE COMMON BLOCKS
 THE "DEL" COMMON BLOCK CONTAINS THE RADIAL AND AXIAL
 INCREMENTAL LENGTHS "DELX" AND "DELY", AND THE
 INCREMENTAL TIME "DELZ"
 THE "COORD" COMMON BLOCK CONTAINS THE RADIAL AND AXIAL
 COORDINATES X AND Y OF THE PRESSURE NODES
 THE "AIR V" COMMON BLOCK CONTAINS THE ARRAY OF AXIAL
 AND RADIAL VELOCITIES AT THE PREVIOUS ITERATION
 THE RADIAL VELOCITY ARRAY VR IS AX BY CY
 THE AXIAL VELOCITY ARRAY VZ IS AX BY CY
 THE "PERIODS" COMMON BLOCK CONTAINS THE PERIODS
 NUMBER OF AVERAGING
 THE "SOURCE" COMMON BLOCK CONTAINS THE SOURCE TERMS OF THE
 CONTINUITY EQUATIONS

C**ALSO REQUIRED AS INPUT FOR THIS SUBROUTINE ARE THE SET
C OF EQUATION SUBPROGRAMS WHICH CALCULATE THE SQUARE OF THE
C VELOCITIES, AND THE CROSS MULTIPLICATION OF THE VELOCITIES.
C THESE ARE GIVEN AFTER THE SUBROUTINE PSORC

C**SUBROUT

C "VR" AND "VZ" ARE THE UPDATED ARRAYS OF RADIAL AND
C AXIAL VELOCITY

C*****

C CALCULATE VELOCITIES AT INTERIOR POINTS
C CALCULATE THE AXIAL COMPONENT OF VELOCITY

DO 10 I=2,NX-1

DO 20 J=2,NY-1

C UPWARD DIFFERENCING

VR(I,J)=.25*(VR(I,J-1)+VR(I,J)+VR(I+1,J)+VR(I+1,J-1))

IF (VR(I,J)-VR(I,J-1))/DELX

IF (VR(I,J)-VR(I,J-1))/DELY

DEKXZ=(VR(I,J)-VR(I,J-1))/DELY

IF (VZ(I,J).GT.0.)DEPVZ=(VZ(I,J+1)-VZ(I,J))/DELY

VZ(I,J)=VZ(I,J)

IF (VZ(I,J).GT.0.)VZ(I,J)=.5*(VZ(I,J+1)+VZ(I,J-1))

VZ(I,J)=VZ(I,J)

1+DELI+(C-VR(I,J)+DEKXZ-VZ(I,J)*DEKXZ

2-(V(I,J)-V(I,J-1))/DELY+(1./RF)*(VZ(I+1,J)-

3VZ(I-1,J))/(X(I)+2.*DELY)+(VZ(I+1,J)-2.*VZ(I,J)+

4VZ(I-1,J))/DELY**2+(VZ(I,J+1)-2.*VZ(I,J)+VZ(I,J-1))

5/DELI**2)+F2(I,J-1))

C CONTINUE

10 CONTINUE

C CALCULATE THE RADIAL COMPONENT OF VELOCITY

DO 20 I=2,NX

DO 20 J=2,NY-1

C UPWARD DIFFERENCING

VZ(I,J)=.25*(VZ(I,J-1)+VZ(I,J)+VZ(I+1,J)+VZ(I+1,J-1))

IF (VZ(I,J)-VZ(I,J-1))/DELY

IF (VZ(I,J)-VZ(I,J-1))/DELY

DEKYZ=(VZ(I,J)-VZ(I,J-1))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

IF (VR(I,J).GT.0.)DEKYZ=(VR(I,J+1)-VR(I,J))/DELY

20 CONTINUE

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C      CALCULATE VELOCITIES AT BOUNDARIES
C**CALCULATE SOLUTION ON LEFT BOUNDARY
C      ZERO SHEAR STRESS ON AXIS OF SYMMETRY
C      DVZ/DZ=0.
      DO 30 J=2,NY
      VZ0(1,J)=(4.*VZ0(2,J)-VZ0(3,J))/3.
30    CONTINUE
C      NORMAL DERIVATIVE OF VELOCITY IS ZERO
      DO 40 J=2,NY-1
      VR0(1,J)=-VR0(2,J)
40    CONTINUE
C**CALCULATE SOLUTION AT BOTTOM BOUNDARY
C      AXIAL VELOCITY =0. SOLID BOUNDARY
      DO 50 I=1,NX
      VZ0(1,I+1)=-VZ0(1,I)
      VZ0(1,IY+1)=0.
50    CONTINUE
C      RADIAL VELOCITY =0. NO SLIP CONDITION
      DO 60 I=1,NX+1
      VR0(1,IY)=0.
60    CONTINUE
C**CALCULATE SOLUTION AT TOP BOUNDARY
C      AXIAL VELOCITY =0. SOLID BOUNDARY
      DO 90 I=1,NX
      VZ0(1,I)=-VZ0(1,2)
90    CONTINUE
C      RADIAL VELOCITY =0. NO SLIP CONDITION
      DO 100 I=1,NX+1
      VR0(1,I)=0.
100   CONTINUE
C**CALCULATE SOLUTION AT RIGHT BOUNDARY
C      MASS CONSERVATION
      DO 70 J=2,NY
      VR0(NX+1,J)=VR0(NX,J)*(X(NX-1)+VELX/2.)/(X(NX)+DELX/2.)
70    CONTINUE
C      NO VELOCITY
      DO 80 J=2,NY-1
      VZ0(NX,J)=VZ0(NX-1,J)+(VR0(NX,J)-VR0(NX,J-1))*DELX/DELX
C      NO AXIAL VELOCITY
      VZ0(NX,J)=0.
80    CONTINUE
      PRINT
      END

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PARTCL SUBROUTINE

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100 SUBROUTINE PARTCL(P,Z,I,UR,UZ,DT,THETA0,FRACO)
200 DIMENSION UR(50),UZ(50),I(50),R(50),Z(50)
300 DIMENSION FORC(50),FORCEZ(50)
400 DIMENSION FR(50,50),FZ(50,50)
500 COMMON /DEL/ DELX,DELT
600 COMMON /SPRAY DIM/ ZL,n,RL,RP,G,PO
700 COMMON /REYNOLDS/ RE
800 COMMON /SOURCE/ FR,FC
900 REAL R,n
1000 PI=3.14159
1100 *****
1200 C THIS SUBROUTINE CALCULATES THE PARAMETERS OF THE LIQUID
1300 C PHASE, NAMELY THE PARTICLE TRAJECTORIES, THE PARTICLE
1400 C VELOCITY ALONG THE TRAJECTORY, AND THE EXCHANGE OF MOMENTUM
1500 C TO THE GAS PHASE (THE SOURCE TERMS).
1600 C
1700 C THESE CALCULATIONS ARE MADE BY INTEGRATING THE EQUATIONS OF
1800 C MOTION OF THE PARTICLES, AND DETERMINING THE NET DRAG FORCE
1900 C ACTING ON THE PARTICLES IN A GIVEN VOLUME.
2000 C A FOURTH ORDER INTEGRATION IS USED FOR THE INTEGRATION OF
2100 C THE EQUATIONS OF MOTION.
2200 C
2300 C NOTE: THIS PROGRAM IS SET UP ONLY FOR THE CASE WHERE THE NOZZLE
2400 C POSITION CORRESPONDS WITH A PRESSURE NODE LOCATION
2500 C
2600 C ***INPUT TO THIS PROGRAM IS AS FOLLOWS:
2700 C
2800 C "DP" - PARTICLE DIAMETER / NOZZLE DIAMETER
2900 C "THETA0" - THE INITIAL HALF ANGLE OF THE SPRAY AT THE
3000 C EJECTION POINT
3100 C "FRACO" - IS THE FRACTION OF MASS FLOW OF EACH PARTICULAR
3200 C TRAJECTORY OR DROPLET SIZE
3300 C
3400 C ***INPUT THROUGH COMMON BLOCK
3500

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3600 THE "SPRAY DIA" COMMON BLOCK CONTAINS THE PARAMETERS OF THE
3700 SPRAY
3800
3900 "ZL"-THE AXIAL LENGTH OF THE DOMAIN DIVIDED BY THE HEIGHT OF
4000 SPRAY
4100 "H"-TURNS ONE FOR A DOWNWARD FACING SPRAY
4200 "RL"-THE RADIAL LENGTH OF THE DOMAIN DIVIDED BY THE HEIGHT OF
4300 THE SPRAY
4400 "RP"-HEIGHT OF THE SPRAY FROM GROUND / NOZZLE DIAMETER
4500 "IG"-INVERSE FROUDE NUMBER SQUARED
4600 "G"-ACCELERATION OF GRAVITY*HEIGHT OF SPRAY/EJECTION VELOCITY**2
4700 "RU"-DENSITY OF GAS/DENSITY OF LIQUID
4800
4900 THE "DEL" COMMON BLOCK CONTAINS THE RADIAL AND AXIAL INCREMENTAL
5000 DISTANCE AND (THROUGH NOT USED IN THIS SUBROUTINE) THE INCREMENTAL
5100 TIME
5200
5300 THE "REYNOLDS" COMMON BLOCK CONTAINS THE REYNOLDS NUMBER OF
5400 NONDIMENSIONALIZATION - EJECTION VELOCITY*SPRAY HEIGHT/GAS
5500 VISCOSITY
5600
5700 **OUTPUT
5800
5900 "Z" AND "R" ARE THE ARRAYS CONTAINING THE AXIAL AND RADIAL
6000 COMPONENTS OF THE PARTICLE TRAJECTORIES
6100
6200 "UZ" AND "UR" ARE THE ARRAYS CONTAINING THE AXIAL AND RADIAL
6300 COMPONENTS OF THE SPRAY VELOCITY ALONG THE SPRAY TRAJECTORY
6400 **OUTPUT INTO COMMON BLOCK
6500
6600 THE "SOURCE" COMMON BLOCK CONTAINS THE TWO DIMENSIONAL
6700 ARRAY OF THE RADIAL AND AXIAL SOURCE TERMS "FR" AND "FZ"
6800
6900 C*****
7000 DELZ=DELX/2.
7100
7200 DOY=IFIX(ZL/DELZ)
7300 DX=IFIX(RL/DELX)+1
7400 DY=IFIX(ZL/DELX)+1
7500 C*****
7600 C*****
7700 C*****
7800 C*****
7900 C*****
8000 C*****
8100 C*****
8200 C*****

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8300      F(1)=0.
8400      Z(1)=0.
8500      CONST=.75*RO*HP**2/(DP**2*RL)
8600      CCONST2=1.5/(CP**3*HP**2)
8700      DO 10 I=1,UNIT
8800          C      START FIRST STEP OF RUNGE-KUTTA INTEGRATION
8900          EKO=DELZ*(UR(1)/UZ(1))
9000          IFO=DELZ/UZ(1)
9100          C      CALCULATE AIRFIELD VELOCITY
9200          CALL AIRVEL(U(1),Z(1),VR,VZ)
9300          REYOLD=RE*DP*SQRT((UR(1)-VR)**2+(UZ(1)-VZ)**2)/HP
9400          C2=-CD(PEYOLD)*REYOLD*CONST
9500          URK0=DELZ*(C2*(UR(1)-VR))/UZ(1)
9600          UZK0=DELZ*(C2*(UZ(1)-VZ)+G)/UZ(1)
9700          C      START SECOND STEP OF RUNGE-KUTTA INTEGRATION
9800          UR1=UR(1)+URK0/2.
9900          UZ1=UZ(1)+UZK0/2.
10000          KR1=DELZ*(UR1/UZ1)
10100          KR1=DELZ/UZ1
10200          R1=UR(1)+KR1/2.
10300          Z1=Z(1)+DELZ/2.
10400          C      CALCULATE AIRFIELD VELOCITY
10500          CALL AIRVEL(R1,Z1,VR,VZ)
10600          REYOLD=RE*DP*SQRT((UR1-VR)**2+(UZ1-VZ)**2)/HP
10700          C2=-CD(PEYOLD)*REYOLD*CONST
10800          UR1=DELZ*(C2*(UR1-VR))/UZ1
10900          UZ1=DELZ*(C2*(UZ1-VZ)+G)/UZ1
11000          C      START THIRD STEP OF RUNGE-KUTTA INTEGRATION
11100          UR1=UR(1)+URK1/2.
11200          UZ1=UZ(1)+UZK1/2.
11300          KR2=DELZ*(UR1/UZ1)
11400          KR2=DELZ/UZ1
11500          R1=UR(1)+KR2/2.
11600          C      CALCULATE AIR FIELD VELOCITY
11700          CALL AIRVEL(R1,Z1,VR,VZ)
11800          REYOLD=RE*DP*SQRT((UR1-VR)**2+(UZ1-VZ)**2)/HP
11900          C2=-CD(PEYOLD)*REYOLD*CONST
12000          UR1=DELZ*(C2*(UR1-VR))/UZ1
12100          UZ1=DELZ*(C2*(UZ1-VZ)+G)/UZ1
12200          C      START FOURTH STEP OF RUNGE-KUTTA INTEGRATION
12300          UR1=UR(1)+URK2
12400          UZ1=UZ(1)+UZK2
12500          KR3=DELZ*(UR1/UZ1)
12600          KR3=DELZ/UZ1
12700          R1=UR(1)+KR3
12800          Z1=Z(1)+DELZ

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12900 C
13000 CALL ALPHVEL(R1,Z1,VK,VZ)
13100 REYOLD=RE*DP*SQRT((UR1-VK)**2+(UZ1-VZ)**2)/HP
13200 C2=-CD(REYOLD)*REYNOLD*CONST
13300 URK3=DELZ*(C2*(UR1-VK))/UZ1
13400 UZK3=DELZ*(C2*(UZ1-VZ)+G)/UZ1
13500 C CALCULATE VALUE AT END OF INTEGRATION STEP
13600 R(1+1)=R(1)+(1./6.)*(URK0+2.*URK1+2.*URK2+URK3)
13700 R(1+1)=R(1)+(1./6.)*(URK0+2.*URK1+2.*URK2+URK3)
13800 UR(1+1)=UR(1)+(1./6.)*(URK0+2.*URK1+2.*URK2+URK3)
13900 UZ(1+1)=UZ(1)+(1./6.)*(UZK0+2.*UZK1+2.*UZK2+UZK3)
14000 Z(1+1)=Z(1)+DELZ
14100 CONTINUE
14200 10 CALCULATION OF TRAJECTORY AND VELOCITIES ALONG TRAJECTORY
14300 C COMPLETE
14400 C *****
14500 C CALCULATE NONDIMENSIONAL FORCE COEFFICIENTS ALONG THE
14600 C TRAJECTORY
14700 C *****
14800 CALL AIRVEL(R(1),Z(1),VK,VZ)
14900 VTOT=SQRT((UR(1)-VK)**2+(UZ(1)-VZ)**2)
15000 REYOLD=RE*DP*VTOT/HP
15100 FORCER(1)=-CD(REYOLD)*VTOT*(UR(1)-VK)*HP*PI*DP**2/8.
15200 FORCEZ(1)=-CD(REYOLD)*VTOT*(UZ(1)-VZ)*HP*PI*DP**2/8.
15300 CALL AIRVEL(R(1),Z(1),VK,VZ)
15400 VTOT=SQRT((UR(1)-VK)**2+(UZ(1)-VZ)**2)
15500 REYOLD=RE*DP*VTOT/HP
15600 FORCER(1+1)=-CD(REYOLD)*VTOT*(UR(1+1)-VK)*HP*PI*DP**2/8.
15700 FORCEZ(1+1)=-CD(REYOLD)*VTOT*(UZ(1+1)-VZ)*HP*PI*DP**2/8.
15800 C1=PI*VTOT**3/(6.*HP)
15900 DO 30 J=2,NUMY
16000 FORCER(J)=C1*(UZ(J)*(UR(J+1)-UR(J-1))/(2.*DELZ)-G)
16100 FORCER(J)=C1*(UZ(J)*(UR(J+1)-UR(J-1))/(2.*DELZ))
16200 CONTINUE
16300 C *****
16400 C CALCULATE SOURCE TERMS IN EACH CONTROL VOLUME
16500 C *****
16600 IFR1=1
16700 JFR1=IFIX((ZL-H)/DELZ+.5)+1
16800 IFZ1=1
16900 JFZ1=IFIX((ZL-H)/DELZ)+1
17000 DO 50 J=1,NUMY

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17100 JFRZ=IFIX((ZL-H+Z(J+1))/DELX+.5)+1
17200 JFR2=IFIX(R(J+1)/DELA)+1
17300 FZAVE=(FUNCEZ(J)+FUNCEZ(J+1))/2.
17400 JFZ2=IFIX((ZL-H+Z(J+1))/DELY)+1
17500 JFZ2=IFIX(R(J+1)/DELA+.5)+1
17600 FZAVE=(FUNCEZ(J)+FUNCEZ(J+1))/2.
17700 TOL=SQRT((R(J+1)-R(J))**2+(Z(J+1)-Z(J))**2)
17800 ICPUSR=JFR2-JFR1+1
17900 ICRUS2=JFZ2-JFZ1+1
18000 DO 60 I=1,ICPUSR
18100 DEL1K=R(J+1)-R(J)
18200 DEL1B=FLOAT(IFR1)*DELA-R(J)+DELA*FLOAT(I-1)
18300 DEL1E=R(J+1)-FLOAT(IFR2-1)*DELA+DELA*FLOAT(ICRUSR-I)
18400 DEL1R=DELA
18500 IF(DEL1K.GT.DEL1R)DEL1R=DEL1K
18600 IF(DEL1B.GT.DEL1R)DEL1R=DEL1B
18700 IF(DEL1R.GT.DEL1E)DEL1E=DEL1R
18800 SCALE=1.
18900 IF(ABS(R(J+1)-R(J)).GT.0.)SCALE=DEL1R/(R(J+1)-R(J))
19000 DEL1Z=SCALE*DELZ
19100 DT=DEL1Z/((JZ(J)+JZ(J+1))/2.)
19200 FE(IFR1+1-1,JFR1)=FE(IFR1+1-1,JFR1)-FZAVE*DT*FRACQ*CONST2/
19300 1((2.*DELA*FLOAT(IFR1+1-2)+DELA)*PI*DELA*DELZ)
19400 CONTINUE
19500 JFR1=JFR2
19600 DO 70 I=1,ICRUS2
19700 JFLFR=R(J+1)-R(J)
19800 DEL1B=(FLOAT(IFZ1)-.5)*DELA-R(J)+DELA*FLOAT(I-1)
19900 DEL1E=R(J+1)-FLOAT(IFZ2-1)*DELA+DELA*FLOAT(ICRUS2-I)
20000 DEL1R=DELA
20100 IF(DEL1B.GT.DEL1R)DEL1R=DEL1B
20200 IF(DEL1E.GT.DEL1R)DEL1R=DEL1E
20300 IF(DEL1R.GT.DEL1E)DEL1E=DEL1R
20400 SCALE=1.
20500 IF(ABS(R(J+1)-R(J)).GT.0.)SCALE=DEL1R/(R(J+1)-R(J))
20600 DEL1Z=SCALE*DELZ
20700 DT=DEL1Z/((JZ(J)+JZ(J+1))/2.)
20800 F1=.5+FLOAT(IFZ1+1-3)
20900 F1=MAX(0.,F1)*DELA
21000 F2=(.5+FLOAT(IFZ1+1-2))*DELA
21100 F2(IFZ1+1-1,JFZ1)=F2(IFZ1+1-1,JFZ1)-FZAVE*DT*FRACQ*CONST2/
21200 1((PI*(F2+2-KI**2)*DELZ)
21300 CONTINUE
21400

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60

70

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21500 JFZ1=JFZ2
21600 IFZ1=IFZ2
21700 CONTINUE
21800 RETURN
21900 END
22000 C THIS FUNCTION SUBPROGRAM GIVES THE DRAG COEFFICIENT
22100 OF A SPHERE AS A FUNCTION OF REYNOLDS NUMBER
22200 OF FUNCTION CD(RL)
22300 CD=(24./RE)+0.6/(1.+50*1/(RE))+.4
22400 RETURN
22500 END
22600 C THIS SUBROUTINE CALCULATES THE AXIAL AND RADIAL COMPONENTS
22700 OF AIR VELOCITY AT POINTS INTERIOR TO THE SAC CPLE, BY
22800 INTERPOLATING THE DISCRETIZED MAC CELL VELOCITIES
22900 SUBROUTINE AIRVEL(R,Z,VKDFRZ,VZDFRZ)
23000 DIMENSION VR(50,50),VZ(50,50)
23100 COMMON /DEL/ DELX,DELY,DELT
23200 COMMON /AIR V/ VZ,VR
23300 COMMON /SPRAY DLE/ ZL,H,RL,HE,G,R0
23400 REAL H,DE
23500 IVR=IFIX(R/DELX+.5)+1
23600 JVR=IFIX((ZL-H+Z)/DELY)+1
23700 IVZ=IFIX(R/DELX)+1
23800 IX=(R/DELX+.5-FLDZ)/DELY+.5)+1
23900 IY=(ZL-H+Z)/DELY-FLDZ(JVR)+1.)*DELY
24000 VKDFRZ=VR(IVR,JVR)+(VR(IVR+1,JVR)-VR(IVR,JVR))*DX/DELX
24100 1+(VR(IVR,JVR+1)-VR(IVR,JVR))*DY/DELY
24200 IX=(R/DELX-FLDZ)/DELY+.5)+DELY
24300 IY=(ZL-H+Z)/DELY+.5-FLDZ(JVZ)+1.)*DELY
24400 VZDFRZ=VZ(IVZ,JVZ)+(VZ(IVZ+1,JVZ)-VZ(IVZ,JVZ))*DX/DELX
24500 1+(VZ(IVZ,JVZ+1)-VZ(IVZ,JVZ))*DY/DELY
24600 RETURN
24700 END
24800

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INPUT FILE

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100 INPUT FOR SPRAY PROGRAM
200 FUELER DIMENSIONS
300 ENTER RADIAL AND AXIAL DUEATH DIMENSIONS; RU AND ZL;
400 NUMBER OF STABILIZATION STEPS BY THE SPRAY HEIGHT
500 1XXXXXXXXXX22XXXXXXXXXXXXX
600 1.
700 ENTER SPRAY HEIGHT/SPRAY LENGTH, H, AND SPRAY LENGTH/NOZZLE DIAMETER, RP
800 1XXXXXXXXXX22XXXXXXXXXXXXX
900 1.
1000 454.55
1100 ENTER NUMBER OF PARTICLE SIZES OR TRAJECTORIES
1200 1XX
1300 4
1400 ENTER DROPLET DIAMETER/NOZZLE DIAMETER, DP, INITIAL ANGLE OF SPRAY,
1500 THEIA), AND VOLUME FLOW FRACTION OF EACH PARTICULAR TRAJECTORY, FRACO
1600 1XXXXXXXXXX22XXXXXXXXXX22XXXXXXXXXXXXX
1700 .09091 .5236 .1667
1800 .09091 .4495 .3333
1900 .09091 .3217 .3333
2000 .09091 .0
2100 ENTER INVERSE FROUDE NUMBER**2 ,G, AND REYNOLDS NOF OF LIQUID, RE
2200 1XXXXXXXXXX22XXXXXXXXXXXXX
2300 .03636 309/300
2400 ENTER DENSITY OF GAS/DENSITY OF LIQUID, RO
2500 1XXXXXXXXXX
2600 .0012024
2700 ENTER TIME STEP, DELT, SUBJECT TO STABILITY RESTRICTIONS
2800 1XXXXXXXXXX
2900 0.02
3000 ENTER NUMBER OF ITERATIONS OF FAC METHOD
3100 1XXXXXXXXXX
3200 1000
3300 ENTER SWITCH FOR INITIAL SOLUTION (0=NONE, 1=IN FILE 19)
3400 1X
3500 0
3600 ENTER NUMBER OF PRESSURE COUFS IN RADIAL AND AXIAL DIRECTIONS
3700 6X
3800 11
3900 11

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RADIAL LENGTH=	1.00000	AXIAL LENGTH=	1.00000	
SPRAY HEIGHT=	1.00000	SPRAY LENGTH TO	NOZZLE DIAMETER	RATIO= 154.54999
NUMBER OF PARTICLES/TRAJECTORY=	4			
NOZZLE DIAMETER/NOZZLE DIAMETER=	0.09091	HALF ANGLE OF SPRAY=	0.52336	
DROPLET DIAMETER/NOZZLE DIAMETER=	0.09091	HALF ANGLE OF SPRAY=	0.34035	
DROPLET DIAMETER/NOZZLE DIAMETER=	0.09091	HALF ANGLE OF SPRAY=	0.32111	
DROPLET DIAMETER/NOZZLE DIAMETER=	0.09091	HALF ANGLE OF SPRAY=	0.00000	
INVERSE FROUDE NUMBER SQUARE=	0.03036	REYNOLDS NUMBER OF LIQUID=	0.00120	
DENSITY OF GAS/DENSITY OF LIQUID=	0.0200000			
TIME STEP =	0.0200000			
NUMBER OF ITERATIONS=	1000			
NODE LOCATION	PRESOURCE			
			MODE LOCATION	AXIAL

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FALLAL POSITION	NODE LOCATION		AXIAL VELOCITY	NODE LOCATION		AXIAL VELOCITY
	FALLAL POSITION	AXIAL POSITION		FALLAL POSITION	AXIAL POSITION	
-0.00264	0.00000	0.00000	-0.01625	-0.05000	0.00000	0.00000
-0.00284	0.00000	0.00000	-0.01219	0.05000	0.00000	0.00000
-0.00046	0.00000	0.00000	0.00000	0.15000	0.00000	0.00000
-0.00018	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000
-0.00008	0.00000	0.00000	0.00000	0.35000	0.00000	0.00000
-0.00004	0.00000	0.00000	0.00000	0.45000	0.00000	0.00000
-0.00002	0.00000	0.00000	0.00000	0.55000	0.00000	0.00000
-0.00001	0.00000	0.00000	0.00000	0.65000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.75000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.85000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.95000	0.00000	0.00000
0.00000	0.00000	0.00000	0.00000	1.05000	0.00000	0.00000
-0.00264	0.00000	0.00000	0.01625	-0.05000	0.01505	0.01505
-0.00284	0.00000	0.00000	0.01219	0.05000	0.00000	-0.01505
-0.00046	0.00000	0.00000	0.00000	0.15000	0.00000	-0.05192
-0.00018	0.00000	0.00000	0.00000	0.25000	0.00000	-0.02955
-0.00008	0.00000	0.00000	0.00000	0.35000	0.00000	-0.02035
-0.00004	0.00000	0.00000	0.00000	0.45000	0.00000	-0.01550
-0.00002	0.00000	0.00000	0.00000	0.55000	0.00000	-0.01259
-0.00001	0.00000	0.00000	0.00000	0.65000	0.00000	-0.01060
0.00000	0.00000	0.00000	0.00000	0.75000	0.00000	-0.00929
0.00000	0.00000	0.00000	0.00000	0.85000	0.00000	-0.00822
0.00000	0.00000	0.00000	0.00000	0.95000	0.00000	-0.00736
0.00000	0.00000	0.00000	0.00000	1.05000	0.00000	-0.00666
-0.00108	0.00000	0.00000	0.11301	-0.05000	0.00000	0.01106
-0.00108	0.00000	0.00000	0.08427	0.05000	0.20000	-0.01106
-0.00040	0.00000	0.00000	-0.00196	0.15000	0.20000	-0.03635
-0.00017	0.00000	0.00000	-0.00086	0.25000	0.20000	-0.02836
-0.00004	0.00000	0.00000	-0.00036	0.35000	0.20000	-0.02022
-0.00002	0.00000	0.00000	-0.00011	0.45000	0.20000	-0.01567
-0.00001	0.00000	0.00000	0.00001	0.55000	0.20000	-0.01244
0.00000	0.00000	0.00000	0.00005	0.65000	0.20000	-0.01101
0.00000	0.00000	0.00000	0.00003	0.75000	0.20000	-0.00963
0.00000	0.00000	0.00000	0.00001	0.85000	0.20000	-0.00853
0.00000	0.00000	0.00000	0.00000	0.95000	0.20000	-0.00764
0.00000	0.00000	0.00000	0.00000	1.05000	0.20000	-0.00692

0.00000	0.30000	-0.00007	0.00000	0.25000	0.17002	-0.05000	0.30000	-0.00538
0.10000	0.30000	-0.00007	0.10000	0.25000	0.13499	0.05000	0.36000	-0.00538
0.20000	0.30000	-0.00007	0.20000	0.25000	0.00612	0.15000	0.30000	-0.01657
0.30000	0.30000	-0.00016	0.30000	0.25000	-0.00088	0.25000	0.30000	-0.02934
0.40000	0.30000	-0.00007	0.40000	0.25000	-0.00043	0.35000	0.30000	-0.01975
0.50000	0.30000	-0.00003	0.50000	0.25000	-0.00000	0.45000	0.30000	-0.01533
0.60000	0.30000	-0.00002	0.60000	0.25000	0.00013	0.55000	0.30000	-0.01282
0.70000	0.30000	-0.00001	0.70000	0.25000	0.00014	0.65000	0.30000	-0.01115
0.80000	0.30000	0.00000	0.80000	0.25000	0.00007	0.75000	0.30000	-0.00949
0.90000	0.30000	0.00000	0.90000	0.25000	0.00002	0.85000	0.30000	-0.00886
1.00000	0.30000	0.00000	1.00000	0.25000	0.00000	0.95000	0.30000	-0.00797
0.00000	0.40000	-0.00004	0.00000	0.35000	0.19849	1.05000	0.30000	-0.00721
0.10000	0.40000	-0.00024	0.10000	0.35000	0.15042	-0.05000	0.40000	-0.00227
0.20000	0.40000	-0.00011	0.20000	0.35000	0.03022	0.05000	0.40000	-0.00227
0.30000	0.40000	-0.00005	0.30000	0.35000	-0.00228	0.15000	0.40000	-0.00558
0.40000	0.40000	-0.00003	0.40000	0.35000	-0.00045	0.25000	0.40000	-0.02288
0.50000	0.40000	-0.00001	0.50000	0.35000	0.00027	0.35000	0.40000	-0.01772
0.60000	0.40000	0.00001	0.60000	0.35000	0.00040	0.45000	0.40000	-0.01459
0.70000	0.40000	0.00001	0.70000	0.35000	0.00038	0.55000	0.40000	-0.01265
0.80000	0.40000	0.00000	0.80000	0.35000	0.00021	0.65000	0.40000	-0.01133
0.90000	0.40000	0.00000	0.90000	0.35000	0.00007	0.75000	0.40000	-0.01029
1.00000	0.40000	0.00000	1.00000	0.35000	0.00000	0.85000	0.40000	-0.00936
0.00000	0.50000	-0.00004	0.00000	0.45000	0.20236	1.05000	0.40000	-0.00848
0.10000	0.50000	-0.00013	0.10000	0.45000	0.16572	-0.05000	0.50000	-0.00767
0.20000	0.50000	-0.00007	0.20000	0.45000	0.05321	0.05000	0.50000	-0.00558
0.30000	0.50000	-0.00003	0.30000	0.45000	-0.00069	0.15000	0.50000	-0.00500
0.40000	0.50000	-0.00002	0.40000	0.45000	0.00046	0.25000	0.50000	-0.01573
0.50000	0.50000	-0.00001	0.50000	0.45000	0.0106	0.35000	0.50000	-0.01031
0.60000	0.50000	0.00001	0.60000	0.45000	0.00114	0.45000	0.50000	-0.01378
0.70000	0.50000	0.00000	0.70000	0.45000	0.00089	0.55000	0.50000	-0.01240
0.80000	0.50000	0.00000	0.80000	0.45000	0.00051	0.65000	0.50000	-0.01151
0.90000	0.50000	0.00000	0.90000	0.45000	0.00018	0.75000	0.50000	-0.01075
1.00000	0.50000	0.00000	1.00000	0.45000	0.00000	0.85000	0.50000	-0.00997
0.00000	0.60000	-0.00004	0.00000	0.55000	0.19907	1.05000	0.50000	-0.00912
0.10000	0.60000	-0.00039	0.10000	0.55000	0.15736	-0.05000	0.60000	-0.00825
0.20000	0.60000	-0.00007	0.20000	0.55000	0.07222	0.05000	0.60000	-0.00746
0.30000	0.60000	-0.00003	0.30000	0.55000	0.00531	0.15000	0.60000	-0.00451
0.40000	0.60000	-0.00002	0.40000	0.55000	0.00101	0.25000	0.60000	-0.00420
0.50000	0.60000	-0.00001	0.50000	0.55000	0.00230	0.35000	0.60000	-0.01459
0.60000	0.60000	0.00001	0.60000	0.55000	0.00225	0.45000	0.60000	-0.01254
0.70000	0.60000	0.00001	0.70000	0.55000	0.00172	0.55000	0.60000	-0.01193
0.80000	0.60000	0.00001	0.80000	0.55000	0.00102	0.65000	0.60000	-0.01125
0.90000	0.60000	0.00001	0.90000	0.55000	0.00039	0.75000	0.60000	-0.01071
1.00000	0.60000	0.00000	1.00000	0.55000	0.00000	0.85000	0.60000	-0.00997
0.00000	0.70000	-0.00004	0.00000	0.65000	0.20000	1.05000	0.60000	-0.00902
0.10000	0.70000	-0.00039	0.10000	0.65000	0.15736	-0.05000	0.70000	-0.00825
0.20000	0.70000	-0.00007	0.20000	0.65000	0.07222	0.05000	0.70000	-0.00746
0.30000	0.70000	-0.00003	0.30000	0.65000	0.00531	0.15000	0.70000	-0.00451
0.40000	0.70000	-0.00002	0.40000	0.65000	0.00101	0.25000	0.70000	-0.00420
0.50000	0.70000	-0.00001	0.50000	0.65000	0.00230	0.35000	0.70000	-0.01459
0.60000	0.70000	0.00001	0.60000	0.65000	0.00225	0.45000	0.70000	-0.01254
0.70000	0.70000	0.00001	0.70000	0.65000	0.00172	0.55000	0.70000	-0.01193
0.80000	0.70000	0.00001	0.80000	0.65000	0.00102	0.65000	0.70000	-0.01125
0.90000	0.70000	0.00001	0.90000	0.65000	0.00039	0.75000	0.70000	-0.01071
1.00000	0.70000	0.00000	1.00000	0.65000	0.00000	0.85000	0.70000	-0.00997

0.00000	0.70000	0.00152	0.00000	0.05000	0.10500	0.05000	0.70000	0.00435
0.10000	0.70000	0.00152	0.00000	0.05000	0.10500	0.05000	0.70000	0.00435
0.20000	0.70000	0.00047	0.00000	0.05000	0.08707	0.05000	0.70000	0.01356
0.30000	0.70000	0.00093	0.00000	0.05000	0.01460	0.05000	0.70000	0.02232
0.40000	0.70000	0.00093	0.00000	0.05000	0.00295	0.05000	0.70000	0.01153
0.50000	0.70000	-0.00001	0.00000	0.05000	0.00413	0.05000	0.70000	0.01000
0.60000	0.70000	-0.00002	0.00000	0.05000	0.00391	0.05000	0.70000	0.01100
0.70000	0.70000	-0.00002	0.00000	0.05000	0.00298	0.05000	0.70000	0.01159
0.80000	0.70000	-0.00002	0.00000	0.05000	0.00184	0.05000	0.70000	0.01184
0.90000	0.70000	-0.00001	0.00000	0.05000	0.00080	0.05000	0.70000	0.01179
1.00000	0.70000	0.00000	0.00000	0.05000	0.00000	0.05000	0.70000	0.01147
0.00000	0.80000	0.00436	0.00000	0.05000	0.15921	0.05000	0.80000	0.01038
0.10000	0.80000	0.00436	0.00000	0.05000	0.14302	0.05000	0.80000	0.00959
0.20000	0.80000	0.00217	0.00000	0.05000	0.09427	0.05000	0.80000	0.00959
0.30000	0.80000	0.00035	0.00000	0.05000	0.02988	0.05000	0.80000	0.03046
0.40000	0.80000	0.00003	0.00000	0.05000	0.00108	0.05000	0.80000	0.01097
0.50000	0.80000	-0.00003	0.00000	0.05000	0.00723	0.05000	0.80000	0.00528
0.60000	0.80000	-0.00004	0.00000	0.05000	0.00039	0.05000	0.80000	0.00838
0.70000	0.80000	-0.00004	0.00000	0.05000	0.00490	0.05000	0.80000	0.00819
0.80000	0.80000	-0.00003	0.00000	0.05000	0.00327	0.05000	0.80000	0.00892
0.90000	0.80000	-0.00003	0.00000	0.05000	0.00178	0.05000	0.80000	0.00961
1.00000	0.80000	0.00000	0.00000	0.05000	0.00000	0.05000	0.80000	0.01137
0.00000	0.90000	0.00865	0.00000	0.05000	0.11267	0.05000	0.90000	0.01024
0.10000	0.90000	0.00865	0.00000	0.05000	0.10401	0.05000	0.90000	0.01687
0.20000	0.90000	0.00551	0.00000	0.05000	0.07801	0.05000	0.90000	0.05109
0.30000	0.90000	0.00222	0.00000	0.05000	0.04244	0.05000	0.90000	0.07159
0.40000	0.90000	0.00059	0.00000	0.05000	0.01955	0.05000	0.90000	0.07511
0.50000	0.90000	0.00016	0.00000	0.05000	0.01168	0.05000	0.90000	0.07005
0.60000	0.90000	0.00000	0.00000	0.05000	0.00820	0.05000	0.90000	0.06440
0.70000	0.90000	0.00000	0.00000	0.05000	0.00629	0.05000	0.90000	0.05954
0.80000	0.90000	-0.00001	0.00000	0.05000	0.00511	0.05000	0.90000	0.05552
0.90000	0.90000	-0.00004	0.00000	0.05000	0.00468	0.05000	0.90000	0.05220
1.00000	0.90000	0.00000	0.00000	0.05000	0.00000	0.05000	0.90000	0.04986
0.00000	1.00000	0.00865	0.00000	0.05000	0.03787	0.05000	1.00000	0.04493
0.10000	1.00000	0.00865	0.00000	0.05000	0.03300	0.05000	1.00000	0.00000
0.20000	1.00000	0.00551	0.00000	0.05000	0.02637	0.05000	1.00000	0.00000
0.30000	1.00000	0.00222	0.00000	0.05000	0.01440	0.05000	1.00000	0.00000
0.40000	1.00000	0.00059	0.00000	0.05000	0.00657	0.05000	1.00000	0.00000
0.50000	1.00000	0.00016	0.00000	0.05000	0.00391	0.05000	1.00000	0.00000
0.60000	1.00000	0.00000	0.00000	0.05000	0.00274	0.05000	1.00000	0.00000
0.70000	1.00000	0.00000	0.00000	0.05000	0.00210	0.05000	1.00000	0.00000
0.80000	1.00000	-0.00001	0.00000	0.05000	0.00170	0.05000	1.00000	0.00000
0.90000	1.00000	-0.00004	0.00000	0.05000	0.00150	0.05000	1.00000	0.00000
1.00000	1.00000	0.00000	0.00000	0.05000	0.00000	0.05000	1.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.05000	0.03787	0.05000	0.00000	0.00000
0.10000	0.00000	0.00865	0.00000	0.05000	0.03300	0.05000	0.00000	0.00000
0.20000	0.00000	0.00551	0.00000	0.05000	0.02637	0.05000	0.00000	0.00000
0.30000	0.00000	0.00222	0.00000	0.05000	0.01440	0.05000	0.00000	0.00000
0.40000	0.00000	0.00059	0.00000	0.05000	0.00657	0.05000	0.00000	0.00000
0.50000	0.00000	0.00016	0.00000	0.05000	0.00391	0.05000	0.00000	0.00000
0.60000	0.00000	0.00000	0.00000	0.05000	0.00274	0.05000	0.00000	0.00000
0.70000	0.00000	0.00000	0.00000	0.05000	0.00210	0.05000	0.00000	0.00000
0.80000	0.00000	-0.00001	0.00000	0.05000	0.00170	0.05000	0.00000	0.00000
0.90000	0.00000	-0.00004	0.00000	0.05000	0.00150	0.05000	0.00000	0.00000
1.00000	0.00000	0.00000	0.00000	0.05000	0.00000	0.05000	0.00000	0.00000

PARTICLE TRAJECTORIES

PARTICLE TRAJECTORY FOR DE=				VOLUME FLOW FRACTION=	
RADIUS	AXIAL DIST	TIME	THETA=	AXIAL VEL	
0.02000	0.00000	0.00000	0.50000	0.52360	0.16670
0.02862	0.05000	0.06294	0.41970	0.86602	
0.05735	0.10000	0.13758	0.35197	0.72934	
0.08535	0.15000	0.22471	0.29072	0.61905	
0.11177	0.20000	0.32512	0.23617	0.53413	
0.13643	0.25000	0.43981	0.19300	0.46584	
0.15916	0.30000	0.57101	0.15540	0.40855	
0.18021	0.35000	0.72201	0.12475	0.35545	
0.19961	0.40000	0.89701	0.09857	0.30839	
0.21736	0.45000	1.10095	0.07656	0.26401	
0.23307	0.50000	1.33558	0.05845	0.22840	
0.24661	0.55000	1.60183	0.04309	0.19965	
0.25798	0.60000	1.90082	0.03260	0.17112	
0.26730	0.65000	2.23161	0.02330	0.15857	
0.27500	0.70000	2.59267	0.01666	0.14454	
0.28158	0.75000	2.98208	0.01184	0.13308	
0.28813	0.80000	3.39359	0.00641	0.12467	
0.29611	0.85000	3.83341	0.00293	0.11600	
0.30690	0.90000	4.29096	0.002845	0.10711	
0.32292	0.95000	4.77512	0.03532	0.09925	
0.34092	1.00000	5.30573	0.03057	0.08600	
PARTICLE TRAJECTORY FOR DE=				0.44050	0.33330
RADIUS	AXIAL DIST	TIME	THETA=	AXIAL VEL	
0.00000	0.00000	0.00000	0.42639	0.40454	
0.02354	0.05000	0.06094	0.36072	0.76728	
0.04698	0.10000	0.13074	0.30519	0.65572	
0.06984	0.15000	0.21273	0.25495	0.56935	
0.09164	0.20000	0.30658	0.21191	0.50007	
0.11210	0.25000	0.41255	0.17579	0.44554	
0.13105	0.30000	0.53115	0.14472	0.39739	
0.14856	0.35000	0.66475	0.11933	0.35446	
0.16475	0.40000	0.81429	0.09804	0.31557	
0.17965	0.45000	0.98270	0.07981	0.28000	
0.19323	0.50000	1.17191	0.06439	0.24950	
0.20544	0.55000	1.38467	0.05141	0.22199	
0.21639	0.60000	1.62110	0.04124	0.20242	
0.22569	0.65000	1.87611	0.03334	0.18705	
0.23425	0.70000	2.15542	0.02746	0.17453	
0.24177	0.75000	2.45991	0.02387	0.16319	
0.24892	0.80000	2.76431	0.02260	0.15560	
0.25694	0.85000	3.09623	0.02614	0.14558	
0.26736	0.90000	3.45099	0.03340	0.13508	
0.28190	0.95000	3.84617	0.03829	0.11662	
0.29837	1.00000	4.29944	0.03262	0.10097	

PARTICLE TRAJECTORY FOR OP=				PARTICLE TRAJECTORY FOR OP=				PARTICLE TRAJECTORY FOR OP=				PARTICLE TRAJECTORY FOR OP=			
RADIUS	AXIAL DIST	TIME	THETA=	RADIUS	AXIAL DIST	TIME	THETA=	RADIUS	AXIAL DIST	TIME	THETA=	RADIUS	AXIAL DIST	TIME	THETA=
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
0.01685	0.05000	0.05797	0.31618	0.05000	0.05393	0.05393	0.00000	0.05000	0.05000	0.05000	0.00000	0.05000	0.05000	0.05000	0.00000
0.03325	0.10000	0.12368	0.26975	0.10000	0.11638	0.11638	0.00000	0.10000	0.10000	0.10000	0.00000	0.10000	0.10000	0.10000	0.00000
0.04950	0.15000	0.20045	0.19448	0.15000	0.16782	0.16782	0.00000	0.15000	0.15000	0.15000	0.00000	0.15000	0.15000	0.15000	0.00000
0.06590	0.20000	0.28769	0.16400	0.20000	0.22615	0.22615	0.00000	0.20000	0.20000	0.20000	0.00000	0.20000	0.20000	0.20000	0.00000
0.07917	0.25000	0.38523	0.13657	0.25000	0.26815	0.26815	0.00000	0.25000	0.25000	0.25000	0.00000	0.25000	0.25000	0.25000	0.00000
0.09349	0.30000	0.49378	0.11659	0.30000	0.35699	0.35699	0.00000	0.30000	0.30000	0.30000	0.00000	0.30000	0.30000	0.30000	0.00000
0.10822	0.35000	0.61114	0.09935	0.35000	0.45370	0.45370	0.00000	0.35000	0.35000	0.35000	0.00000	0.35000	0.35000	0.35000	0.00000
0.11725	0.40000	0.73259	0.08417	0.40000	0.55783	0.55783	0.00000	0.40000	0.40000	0.40000	0.00000	0.40000	0.40000	0.40000	0.00000
0.12879	0.45000	0.87009	0.07153	0.45000	0.66393	0.66393	0.00000	0.45000	0.45000	0.45000	0.00000	0.45000	0.45000	0.45000	0.00000
0.13874	0.50000	1.03015	0.06068	0.50000	0.78065	0.78065	0.00000	0.50000	0.50000	0.50000	0.00000	0.50000	0.50000	0.50000	0.00000
0.14765	0.55000	1.19335	0.05168	0.55000	0.91671	0.91671	0.00000	0.55000	0.55000	0.55000	0.00000	0.55000	0.55000	0.55000	0.00000
0.15639	0.60000	1.36917	0.04414	0.60000	1.04085	1.04085	0.00000	0.60000	0.60000	0.60000	0.00000	0.60000	0.60000	0.60000	0.00000
0.16410	0.65000	1.55801	0.03858	0.65000	1.17692	1.17692	0.00000	0.65000	0.65000	0.65000	0.00000	0.65000	0.65000	0.65000	0.00000
0.17141	0.70000	1.75962	0.03414	0.70000	1.31696	1.31696	0.00000	0.70000	0.70000	0.70000	0.00000	0.70000	0.70000	0.70000	0.00000
0.17841	0.75000	1.97516	0.03111	0.75000	1.46715	1.46715	0.00000	0.75000	0.75000	0.75000	0.00000	0.75000	0.75000	0.75000	0.00000
0.18533	0.80000	2.20404	0.02978	0.80000	1.62213	1.62213	0.00000	0.80000	0.80000	0.80000	0.00000	0.80000	0.80000	0.80000	0.00000
0.19273	0.85000	2.44955	0.03072	0.85000	1.78143	1.78143	0.00000	0.85000	0.85000	0.85000	0.00000	0.85000	0.85000	0.85000	0.00000
0.20120	0.90000	2.71420	0.03391	0.90000	1.95760	1.95760	0.00000	0.90000	0.90000	0.90000	0.00000	0.90000	0.90000	0.90000	0.00000
0.21172	0.95000	3.00950	0.03765	0.95000	2.14341	2.14341	0.00000	0.95000	0.95000	0.95000	0.00000	0.95000	0.95000	0.95000	0.00000
0.22387	1.00000	3.34239	0.03367	1.00000	2.34903	2.34903	0.00000	1.00000	1.00000	1.00000	0.00000	1.00000	1.00000	1.00000	0.00000
0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
0.00001	0.05000	0.05393	0.00000	0.05000	0.05393	0.05393	0.00000	0.05000	0.05000	0.05000	0.00000	0.05000	0.05000	0.05000	0.00000
0.00003	0.10000	0.11638	0.00000	0.10000	0.11638	0.11638	0.00000	0.10000	0.10000	0.10000	0.00000	0.10000	0.10000	0.10000	0.00000
0.00020	0.15000	0.16782	0.00000	0.15000	0.16782	0.16782	0.00000	0.15000	0.15000	0.15000	0.00000	0.15000	0.15000	0.15000	0.00000
0.00028	0.20000	0.22615	0.00000	0.20000	0.22615	0.22615	0.00000	0.20000	0.20000	0.20000	0.00000	0.20000	0.20000	0.20000	0.00000
0.00034	0.25000	0.26815	0.00000	0.25000	0.26815	0.26815	0.00000	0.25000	0.25000	0.25000	0.00000	0.25000	0.25000	0.25000	0.00000
0.00037	0.30000	0.35699	0.00000	0.30000	0.35699	0.35699	0.00000	0.30000	0.30000	0.30000	0.00000	0.30000	0.30000	0.30000	0.00000
0.00047	0.35000	0.45370	0.00000	0.35000	0.45370	0.45370	0.00000	0.35000	0.35000	0.35000	0.00000	0.35000	0.35000	0.35000	0.00000
0.00035	0.40000	0.55783	0.00000	0.40000	0.55783	0.55783	0.00000	0.40000	0.40000	0.40000	0.00000	0.40000	0.40000	0.40000	0.00000
0.00032	0.45000	0.66393	0.00000	0.45000	0.66393	0.66393	0.00000	0.45000	0.45000	0.45000	0.00000	0.45000	0.45000	0.45000	0.00000
0.00027	0.50000	0.78065	0.00000	0.50000	0.78065	0.78065	0.00000	0.50000	0.50000	0.50000	0.00000	0.50000	0.50000	0.50000	0.00000
0.00023	0.55000	0.91671	0.00000	0.55000	0.91671	0.91671	0.00000	0.55000	0.55000	0.55000	0.00000	0.55000	0.55000	0.55000	0.00000
0.00016	0.60000	1.04085	0.00000	0.60000	1.04085	1.04085	0.00000	0.60000	0.60000	0.60000	0.00000	0.60000	0.60000	0.60000	0.00000
0.00010	0.65000	1.17692	0.00000	0.65000	1.17692	1.17692	0.00000	0.65000	0.65000	0.65000	0.00000	0.65000	0.65000	0.65000	0.00000
0.00001	0.70000	1.31696	0.00000	0.70000	1.31696	1.31696	0.00000	0.70000	0.70000	0.70000	0.00000	0.70000	0.70000	0.70000	0.00000
-0.00010	0.75000	1.46715	0.00000	0.75000	1.46715	1.46715	0.00000	0.75000	0.75000	0.75000	0.00000	0.75000	0.75000	0.75000	0.00000
-0.00025	0.80000	1.62213	0.00000	0.80000	1.62213	1.62213	0.00000	0.80000	0.80000	0.80000	0.00000	0.80000	0.80000	0.80000	0.00000
-0.00043	0.85000	1.78143	0.00000	0.85000	1.78143	1.78143	0.00000	0.85000	0.85000	0.85000	0.00000	0.85000	0.85000	0.85000	0.00000
-0.00070	0.90000	1.95760	0.00000	0.90000	1.95760	1.95760	0.00000	0.90000	0.90000	0.90000	0.00000	0.90000	0.90000	0.90000	0.00000
-0.00096	0.95000	2.14341	0.00000	0.95000	2.14341	2.14341	0.00000	0.95000	0.95000	0.95000	0.00000	0.95000	0.95000	0.95000	0.00000
-0.00031	1.00000	2.34903	0.00000	1.00000	2.34903	2.34903	0.00000	1.00000	1.00000	1.00000	0.00000	1.00000	1.00000	1.00000	0.00000

0.32170

VOLUME FLOW FRACTION=

AXIAL VEL

THETA=

0.09091

PARTICLE TRAJECTORY FOR OP=

RADIUS

AXIAL DIST

TIME

THETA=

AXIAL VEL

VOLUME FLOW FRACTION=

0.33330

0.16670

VOLUME FLOW FRACTION=

AXIAL VEL

THETA=

0.09091

PARTICLE TRAJECTORY FOR OP=

RADIUS

AXIAL DIST

TIME

THETA=

AXIAL VEL

VOLUME FLOW FRACTION=

0.16670

DATE
FILMED

05-8